

MEASUREMENT OF THE BEAM ENERGY SPREAD IN THE TTF PHOTO-INJECTOR

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Abstract

At the TESLA Test Facility (TTF) linac the required high peak current for FEL operation is achieved by compressing the beam longitudinally in a magnetic chicane. The peak current after the chicane is determined by the residual energy spread of the electron bunch which is produced by an rf photo-injector. By residual energy spread we refer to the energy spread of a temporal slice of the bunch which can not be compensated by any time dependent energy modulation. To determine the energy distribution, an improved optical system has been implemented to image the beam at an OTR-station after a spectrometer dipole. In this paper the results of the beam profile measurements are presented and compared to particle tracking simulations. It is shown that the residual energy spread in the injector on in order of a few keV only, even at bunch charges of 4 nC.

INTRODUCTION

Most existing and future designs of linac driven Self-Amplified Spontaneous Emission Free-Electron Lasers (SASE-FELs) use high brightness photo-injectors to meet the tight requirements on the transverse and longitudinal beam quality. In a photo-injector, the electrons are produced by impinging a short-pulse laser on a photo-cathode installed in a radio frequency gun which is operated at high gradients. The rapid acceleration in the RF gun is necessary to overcome the strong repulsive space charge forces. Several optimisation steps are required in the design and during operation of a photo-injector to minimise the transverse projected emittance growth. In addition to the transverse emittance, the longitudinal phase space distribution also has major impacts on the linac design and the possibilities to operate a SASE-FEL.

Unlike other sources, such as conventional thermionic injectors or damping rings, the energy of electrons produced in a photo-injector is correlated in time and spread only in a very narrow energy band. The time-energy correlation is mainly caused by the RF curvature and thus is non-linear. In general, the correlation can be linearised by accelerating the beam at higher harmonic frequencies before it is compressed in length [1, 2]. If the correlation is eliminated, the residual energy spread determines the achievable peak current while maintaining an energy spread small enough to operate a SASE-FEL.

At the TESLA Test Facility (TTF), a photo-injector has been used to drive a SASE-FEL operating in the VUV-wavelength range between 80 nm and 180 nm [3]. A detailed description of the experimental facility can be found in [4]. The TTF-FEL consists of a linear accelerator pro-

ducing bunches with an energy up to 300 MeV and a 14.1 m long undulator magnet. The bunches exit the photo-injector with an energy of 16 MeV. At 2.8 nC bunch charge, the rms width of longitudinal charge density is 3.6 mm. The main accelerator contains two superconducting acceleration modules which are separated by a magnetic bunch compressor.

As a consequence of the fairly long bunch length in comparison with the RF wavelength of 23 cm, the rf-induced curvature downstream of the bunch compressor causes a strongly non-Gaussian charge distribution with a narrow leading peak and a long tail (no linearisation). From the experimentally observed FEL radiation the photon pulse duration τ_{rad} has been determined to be less than 50 fs FWHH [5]. The observations are in agreement with particle tracking simulations and numerical simulations of the SASE process. Of the 2.8 nC bunch charge, only the 0.1-0.2 nC contained in the leading spike with a peak current of 1.3 kA contributes to the FEL radiation. The current of trailing electrons is insufficient to initiate the SASE process. The key beam parameter determining the width of the spike $\sigma_{z, spike}$ is the residual (slice) energy spread $\sigma_{E,s}$. Tracking simulations of the photo-injector predict a residual energy spread below 5 keV. However, investigations in the past could only set a lower threshold of 22.1 ± 2.7 keV [6] for the slice energy spread, much too large and in disagreement to the numerical results. To close the gap in understanding, the optical setup and the experimental condition have been improved to yield high precision measurements of the beam energy distribution.

EXPERIMENTAL CONDITIONS

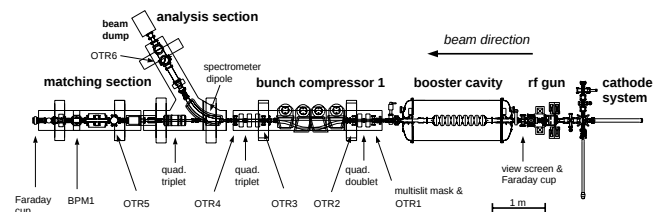


Figure 1: Scheme of the photo-injector.

Figure 1 shows a scheme of the TTF photo-injector. Beam and injector parameters for the experiment and during FEL operation are listed in Tab. 1. The UV-drive laser operates at a wavelength of 262 nm with a pulse energy of 100 μ J. With an ultra-fast streak camera (FESCA-200, Hamamatsu Photonics, Japan) a pulse duration of 7 ± 0.5 ps rms has been measured. The laser pulse shape is Gaus-

sian. The laser spot on the cathode is radially uniform with a diameter of 6 mm. For the experiment, a bunch charge of 4 nC has been adjusted. The 1.3 GHz, 1 1/2-cell room-temperature copper gun has been operated at a gradient of 35 MV/m accelerating the beam to an energy of 3.8 MeV. The nominal gun phase is 40°. A superconducting 9-cell booster cavity rises the beam energy to 16 MeV. Bunch compressor 1, after the booster has been switched off. Using the quadrupole triplet located upstream of the

Table 1: Photo injector and beam parameters

parameter	symbol	value	unit
bunch charge	Q	4	nC
gun gradient	G_{gun}	35	MV/m
gun phase	ϕ_{gun}	30-50	deg.
laser diameter	d	6	mm
laser pulse	σ_t	7	ps
booster gradient	$G_{booster}$	11.5	MV/m
booster phase	$\phi_{booster}$	131-155	deg.
dispersion at OTR6	η_x	1.367	m
beam energy	E	15.4-16.3	MeV
x/y norm. emittance	ϵ_x/ϵ_y	10.6	μm
x/y norm. slice emit.	$\epsilon_{x,s}/\epsilon_{y,s}$	4-14	μm
slice beta-func. OTR6	β_x	7-17	cm
FEL operation			
bunch charge	Q	2.8	nC
gun gradient	G_{gun}	40	MV/m
laser diameter	d	3	mm

spectrometer dipole, the beam is focused onto an optical transition screen (OTR6) situated in the spectrometer beam line. The horizontal dispersion at the screen amounts to 1.37 m. The OTR-screen is rotated by 45° with respect to the y-axis. To correct the depth of field on the entire screen, a shift-tilt objective has been used to image the OTR-light on a 12-bit CCD camera. With horizontal and vertical wires on the screen the magnification is determined to be 32.3 (36.4) μm per CCD-pixel in x (y). By measuring the point spread function of the optical setup a resolution of 44 μm rms has been derived. The exposure time of the CCD camera has been set at its minimum (10 μs) to reduce the counts on the image due to X-rays. Figure 2 shows a typical image of a single bunch. The peak width is proportional to the residual energy spread while the long low energy tail is mainly determined by the phase of the booster cavity. For the measurement, gun and booster cavity phase have been varied. For each new phase setting, the focusing strength of the quadrupole triplet has been corrected to minimize the rising edge of the peak in the energy profile. Phase, amplitude, and charge jitter significantly change the peak profile on shot-to-shot basis. For each setting, 10 images are stored. Altogether about 270 pictures are analyzed.

Simulations

The particle tracking code ASTRA [7] is used to simulate charge distribution produced in the injector. Per run, 4000 macro-particles are tracked providing a sufficiently accurate result within reasonable computation time. Figure 3 shows the longitudinal phase space at the entrance of the spectrometer dipole. The two cases, 4 nC (blue) and 0.01 nC (green), demonstrate the difference between a bunch with high space charge force and one without (thermal emittance is set to zero).

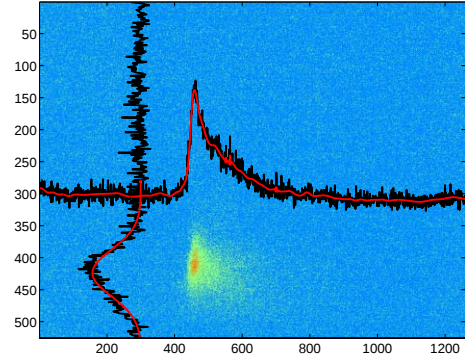
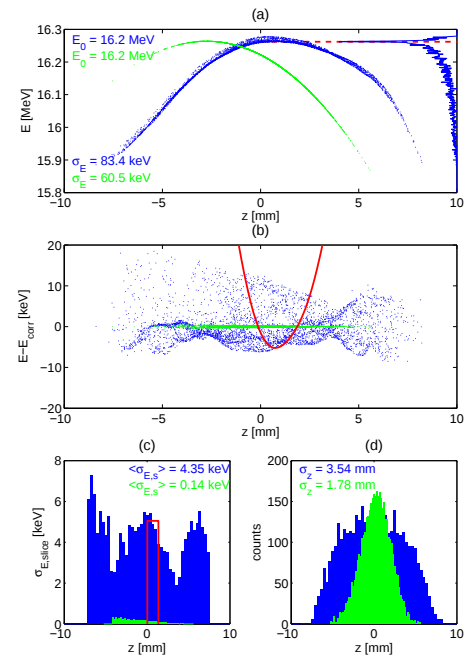


Figure 2: Image of bunch at OTR6.


 Figure 3: Longitudinal phase space distribution ($\sigma_t = 7$ ps, $\phi_{gun} = 40^\circ$, $\phi_{booster} = 145^\circ$).

The rf-induced correlated energy spread is typically 2 orders in magnitude larger than the slice energy spread (see Fig.3(b) and Fig. 3(c)). The cosine-like distribution projected on the energy axis produces a spike at high energies (see Fig. 3(a)). The smaller the residual energy spread, the more pronounced and narrow the spike will be. For the later analysis, we use only the particles with the energies above the peak value of energy spike indicated by a red

dashed line in Fig. 3(a). Due to the RF curvature, particles within the parabolic-like curve plotted in Fig. 3(b) contribute to shape and width of the rising edge of the spike. For the example shown, the longitudinal rms width of these particles is $670 \mu\text{m}$ or $0.2 \cdot \sigma_z$. Figure 3(c) shows that the residual energy spread calculated for particles located in different bunch slices (blue) agree well with the one we are able to measure (red bar). Because the residual energy spread changes with the position z (Fig. 3c) the phase of the booster cavity has been varied in steps of 2° . This allows observation of the residual energy spread at various positions along the bunch.

Image processing and data analysis

The first step in the image processing is the removal of single, high intensity pixels caused by x-rays hitting the CCD. Then, an average of 100 CCD background pictures, showing a small deviation in the read out per pixel, is subtracted. To further improve the quality of the horizontal projection, only the image in a band of $\pm 4\sigma_y$ obtained by fitting a Gaussian to the vertical projection is used. The profile is then filtered using wavelets (sym-lets of 8^{th} order). By filtering that is based on spatial frequency as well as scale, wavelet-filters can significantly reduce noise without obscuring narrow features of the profile, especially the steep rising edge seen at high energies.

The simulation data are treated similarly, only that in this case 0^{th} order wavelets (Haar wavelets) are used to avoid negative values in the profile. Filtering of the simulation data is necessary because of the limited number of particles used for the tracking.

To find the phase offset of the booster cavity, which is a priori unknown, the simulated profiles are fitted to the measured ones by allowing a horizontal and vertical shift as well as vertical scaling. The simulations cover a number of laser pulse lengths and phases. The most likely parameters are found when the sequence of simulated profiles best agrees with the measured ones. The best agreement was found with a laser pulse length of 7 ps. Note that for determining the phase offset, the whole profile is taken into account with a special focus on the low energy tail which is dominated by the rf-curvature and hence best reveals the absolute phase. The residual energy spread is quantified by fitting a Gaussian function to the high energy edge of the profile, where position and height of the maximum are fixed, and only the σ can vary. The results are shown in Fig. 4.

Agreement between measurement and simulations

Figure 4 shows the compilation of the measured and simulated residual energy spread. Besides statistical fluctuations from bunch to bunch, the measurements are influenced by a number of systematic errors. The broadening influence of the rf curvature is present both in the measurement and in the simulation. No significant impact from the

optical resolution of the system is to be expected, whereas the beam optics allow for a resolution slightly below 2 keV. Only for two phase values, 133° and 135° , has a resolution of 2.5 keV been found. The intensity of the beam im-

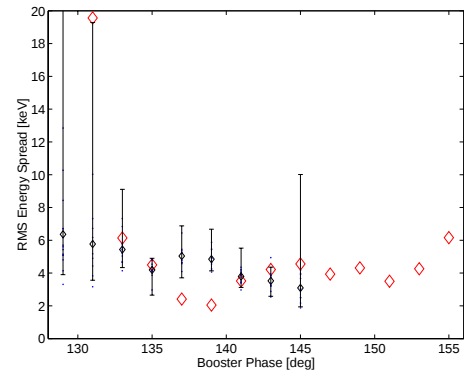


Figure 4: Slice energy spread measurement (points) and simulation (large diamonds).

ages was very limited. After digitisation, even the most intense images deliver pixel readings of only up to three counts above the pedestal of about two counts. This leads to distortion of the results, especially for weaker images. On one hand the height of the profile appears even smaller, which is reflected by the scaling factors needed in the fits that match the expectations. On the other hand this causes much steeper edges in the measured profile than there are in the original distribution. This significantly increases the measurement error towards the ends of the bunch. Taking these effects into account, the simulations reproduce the measurements very nicely.

CONCLUSION

The residual energy spread in a photo injector has been measured with a resolution down to 2 keV ($\sigma_E/E = 1.3 \cdot 10^{-4}$). Utilising the cosine-curvature of the accelerating rf-fields, slice energy spread could be measured. The results are consistent with simulations. The values are close to and below 5 keV. This matches observations made with the TTF SASE-FEL radiation indirectly confirming predicted values.

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