IMPROVED OPERATION OF THE TTF PHOTOINJECTOR FOR FEL OPERATION

S. Schreiber*, J.-P. Carneiro, Ch. Gerth, K. Honkavaara, M. Hüning, Ph. Piot,
E. Schneidmiller, M. Yurkov, DESY, 22603 Hamburg, Germany.

Abstract

The RF gun based photoinjector of the TTF Free Electron Laser (TTF-FEL) at DESY has been optimized to improve the gain of the VUV free electron laser. With the new settings, saturation has been achieved. The actual injector performance in terms of longitudinal and transverse phase space is described.

1 INTRODUCTION

The TESLA Test Facility (TTF) operates an rf gun based photoinjector [1]. Among various experiments for the TESLA project, the photoinjector is used to drive the TTF-FEL free electron laser, where excellent beam properties are essential. It requires sub-picosecond electron bunches with high peak current, small transverse emittance in both planes while keeping the energy spread small [2]. Recently, the TTF-FEL achieved saturation in the VUV wavelength region [3]. This has been obtained with injector beam parameters, which differ from the design. This report describes these differences and points out, that even with a reduced performance of the electron source in terms of longitudinal and transverse emittance, it is possible to tune the beam in a way, that parts or slices still meet or even outperform the design.

2 OVERVIEW AND DESIGN

A sketch of the the TTF Linac including the injector is shown in Fig. 1. The electron source is a laser-driven L-band rf gun with a Cs_2Te cathode. The cathode is illuminated by a train of UV laser pulses generated in a mode-locked solid-state laser system synchronized with the rf (1.3 GHz) [4]. The rf gun section is followed by a booster, a standard TESLA 9-cell superconducting accelerating cavity operated at 11.5 MV/m. The beam energy measured at the energy spectrometer is 16.5 MeV. Further details of the injector can be found in [1]. The beam is accelerated by two 12 m long TESLA accelerating modules containing eight 9-cell superconducting accelerating structures each. It is injected into the undulator modules with an energy of up to 300 MeV. Two bunch compressors are installed: BC1 is downstream of the booster cavity, BC2 between the accelerating modules. For more details refer to [3].

The requirements to drive the FEL are tight. The design asks for a high brilliance: high peak current, small transverse emittance in both planes and low energy spread. Due to space charge effects it is not possible to produce the requested peak current of 500 A (phase 1) or 2.5 kA (phase 2) directly at the gun. The design starts with a bunch length of 2 mm at the gun exit, a charge of 1 nC, a normalized emittance of 2 mm mrad, and an uncorrelated energy spread of 25 keV. The bunch is then compressed to 0.8 mm (BC1) prior to acceleration in the first TESLA module. A second compression to 250 μm (BC2) leads to the required peak current. The pre-compression to 0.8 mm is necessary to keep the energy spread required for lasing below $1{\cdot}10^{-3}$ [5]. The injector design parameters for (a) TESLA 500 as defined in [6], (b) the revised TESLA parameters, and the parameters for the TTF-FEL are listed in Table 1.

Table 1: Injector design parameters for TESLA related experiments (TTFL) and TTF-FEL operation. TTFL(a) is the initial TESLA 500 design, TTFL(b) the revised design. Actual operating parameters differ from this table.

Parameter		**TTFL**		**FEL**
		(a)	(b)	
RF frequency	GHz		1.3	
Rep. rate	Hz		10	
Pulse train length	μs		800	
Pulse train current	mA	8	9	9
Bunch frequency	MHz	1	2.25	9
Bunch charge	nC	8	4	1
Bunch length (rms)	mm	1	1	0.8
Emitt. norm. (x,y)	μm	20	10	2
ΔE/E (rms)	%		0.1	
Injection energy	MeV		20	

3 MODIFIED BEAM PARAMETERS

The first bunch compressor (BC1) has been designed to meet TESLA 500 beam specifications in terms of bunch length and transverse emittance as in Table 1(a) [6]. It is able to compress the beam down to 1 mm and less, however, simulation indicate an increase in transverse emittance by a factor of four or more. The simulation of the compressor suffers from complicated space charge effects and does not give reliable predictions of the emittance. Measurements have been performed at the Fermilab/NICADD Photoinjector Laboratory, a twin of the TTF injector. The results are reported in [7].

Initially, parameters of the rf gun have been adjusted to minimize the transverse emittance for the design charge of 1 nC. The gradient on the cathode is 37 MV/m, the relative

* siegfried.schreiber@desy.de

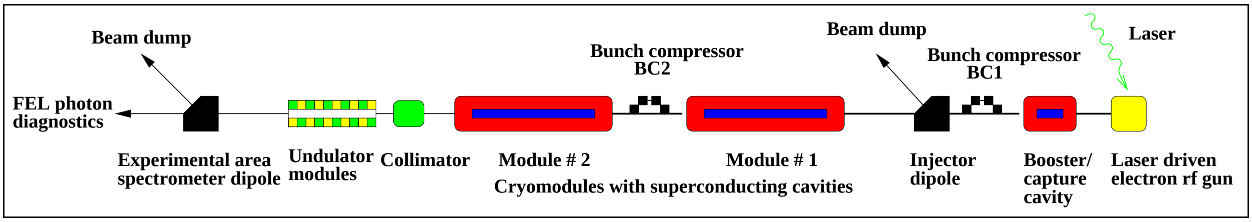

Figure 1: Schematic overview of the TTF-FEL linac (phase 1). Beam direction is from right to left, the total length is 100 m (not to scale).

phase of the gun rf to the laser is chosen to be 40°, the laser spot radius on the cathode is 1.5 mm. The field of the first and second solenoid is 0.105 T and 0.088 T respectively. For this parameters, we measure a transverse emittance of 3.0 ± 0.2 mm mrad [8]. The length of the photoinjector laser pulse is σ_l = 7 ± 1 ps leading to an electron bunch length of σ_z = 3.2 ± 0.2 mm [9]. The energy spread measured with the injector dipole is 22.1 ± 0.3 keV [1].

The measured energy spread is within the design, but the bunch length after the booster is by a factor of 4 too long. A workaround is to take advantage of the initially long bunch. Off crest acceleration with the first TESLA module (to 149 MeV) is required for bunch compression in BC2. Since the bunch length is long compared to the rf wavelength of 23 cm, acceleration induces a curvature in the longitudinal phase space distribution. Because of the small initial uncorrelated energy spread of 20 keV, its projection on the time/phase axis results in a high peak current spike with a long tail. It is therefore possible to not use BC1 at all. This is illustrated in Fig. 2. It shows a simulation [10] of the longitudinal phase space performed with the beam parameters above and nominal compression settings for the second bunch compressor BC2; a bunch charge of 3 nC is used, BC1 switched off. It is in fact this spike which carries the required peak current for lasing. The charge per bunch has been raised from 1 to 3 nC, but the laser spot size on the cathode is kept constant at 1.5 mm radius to keep the emittance small. An increased field on the cathode of 40 MV/m (2.9 MW pulsed rf power), reduces space charge effects and the peak current is further improved. For 3 nC the total rms bunch length increases to 4 mm. A further increase of charge for the given laser spot size and gun gradient is not possible. Saturation of the charge extracted starts already at 3 nC, it is limited to about 4 nC.

With the operation mode described above, the SASE FEL reached saturation [3]. In the following, measurements of the transverse emittance and the longitudinal charge distribution for this operation mode are presented.

4 EXPERIMENTAL SET-UP AND RESULTS

The emittance has been measured with the quadrupole scan method at several places along the linac: downstream the booster cavity at 16.5 MeV, downstream the bunch compressor BC2 at 137 MeV, and at the entrance of the undulator with a beam energy of 246 MeV. In all cases, the beam size is measured as a function of the magnetic gradient of a quadrupole. The emittance is then calculated by fitting the data to the prediction given by beam transport equations. The beam size is measured using optical transition radiation emitted from a thin aluminum layer on kapton and in the case of BC2 on a silicon wafer. The beta-function is adjusted in a way, that spot sizes are never smaller than 100 μm well within the resolution of the camera system of 50 μm.

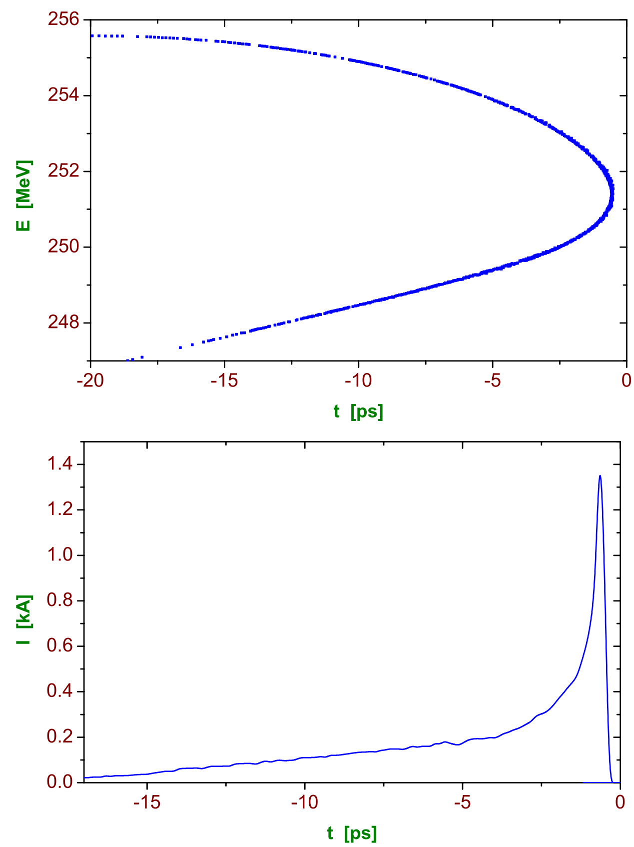

Figure 2: Simulation of the longitudinal phase space after bunch compression (upper) with its projection on the time axis (lower). Beam parameters of the improved operation mode used. Refer to the text for details.

Downstream the booster we measure an emittance of 3.0 (3.2) ± 0.5 mm mrad horizontal (vertical). At 137 MeV we obtain a larger emittance of 8 (9) ± 2 mm mrad. It stays about constant along the linac: at the undulator entrance at 246 MeV the measured value is 11 $\pm$ 6 (7 $\pm$ 2) mm mrad. These numbers are for on-crest acceleration of a single bunch of 1 nC, by-passing BC1, but going through BC2.

With full compression of the beam, it has been observed, that the transverse profile breaks up into two or three bunchlets. This makes it difficult to give a meaningful emittance number. Simply projecting the total beam profile regardless of its structure yields an emittance of 14 (13) $\pm$ 2 mm mrad horizontal (vertical). Increasing the charge increases the measured emittance: for 2 nC we obtain 22 (19) $\pm$ 2 mm mrad. The result agrees roughly with the expectations from simulations (see [8]), however, the beam break up is not yet fully understood.

A drawback of this method is, that it gives the projected emittance of the total bunch rather than the slice emittance of the part of the bunch which actually contributes to lasing. From the measured properties of FEL radiation it is possible to deduce the value of the slice emittance. Using the measured gain length of 67 $\pm$ 5 cm [3] and a peak current in the range of 0.5 to 1 kA we get 4 to 6 mm mrad respectively.

For the bunch length measurements, we use synchrotron radiation emitted by the horizontally deflecting spectrometer dipole after the undulator (see Fig. 1). The light is measured with a streak camera. It has an intrinsic resolution of 210 fs (FWHM) [11]. Details of the set-up are described in [9]. In order to reduce chromatic effects, a narrow-band wavelength filter ($\Delta\lambda$ = 5 nm) has been used. The data presented here are obtained with the second fastest streak speed of 50 ps/10.29 mm, where the resolution is 200 fs sigma. The profiles have been taken when the beam was set-up to provide FEL laser radiation to experiments, close to saturation.

Figure 3 (A) shows an overlay of several measurements of the same longitudinal bunch profile. The average profile is shown in Fig. 3 (B). The profile has a clear leading peak and a long tail. The width of the leading peak is 650 $\pm$ 100 fs (sigma).[1] From the profile, we can estimate, that about 30 % of the charge is contained in the peak. For a total charge of 3 nC, this results in a peak current of 0.6 kA.

For comparison, the profile obtained with tomographic methods [12] is overlaid to the streak camera profile in Fig. 3 (B). The data of both methods agree very well, except that the tomographic data show a larger but shorter tail.

5 DISCUSSION AND CONCLUSION

The original design of the photoinjector for the TTF aimed for TESLA beam parameters. To drive the TTF-FEL, the demands on both, the longitudinal and transverse

[1] It has to be noted, that in the previous measurements it was not possible to resolve this peak due to the limited resolution of the camera available at that time [9]. The rms width over the whole profile of the data presented here is consistent with the previous measurements.

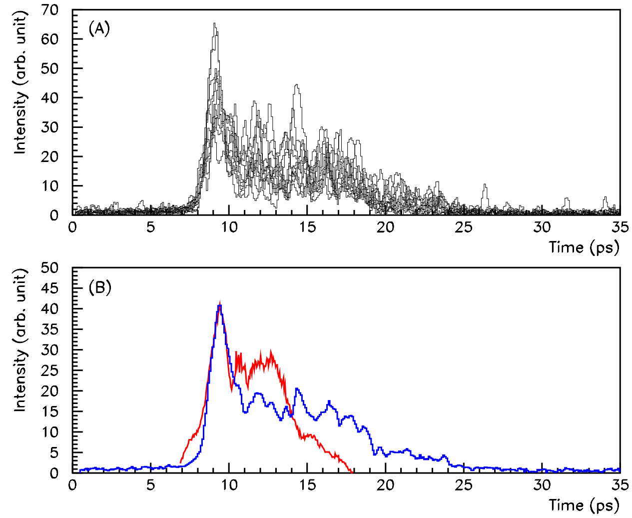

Figure 3: Several measurements of the same longitudinal beam profile obtained with a streak camera (A). The average over all profiles is plotted in (B), blue curve. These data have been taken under beam conditions for lasing close to saturation. For comparison, a profile obtained with tomographic methods is overlaid in (B), red curve.

phase space could not be fulfilled at the same time. Either, the transverse emittance increased for full bunch compression, or the bunches are too long when keeping the transverse emittance small. The solution is to use the effect of rf curvature when accelerating long bunches. After bunch compression, the profile exhibits a peak, which fulfills the requirement for the peak current while keeping the transverse emittance small.

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