PERFORMANCE OF THE TTF PHOTOINJECTOR FOR FEL OPERATION

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The RF gun based photoinjector of the TESLA Test Facility Linac (TTFL) at DESY has been built to produce a beam close to TESLA specifications in order to test superconducting accelerating structures. With the installation of the TTF Free-Electron Laser (TTF-FEL) in the TTF linac, the injector has been gradually optimized to improve the gain of the SASE lasing process and to achieve saturation in the VUV wavelength region. The report describes the performance of the optimized injector in terms of longitudinal and transverse phase space.

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. To do this, excellent beam properties are essential. It requires a train of electron bunches, where each bunch has a high peak current in the kA range, a small transverse emittance in both planes in the order of a μm, and a small uncorrelated energy spread below 0.1 %[2]. Recently, the TTF-FEL achieved saturation in the VUV wavelength region (80 to 100 nm)[3]. One key issue for this success was the tuning of injector beam parameters. The optimized parameters differ from the design. In the following, the most relevant differences are described.

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 1 1/2-cell 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

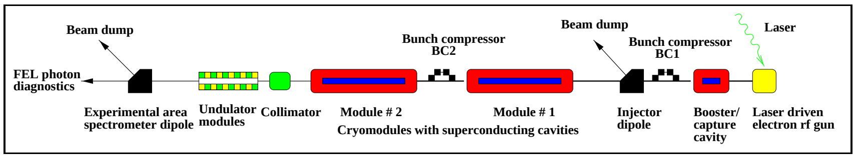

Figure 1. Schematic overview of the TTF-FEL linac phase 1 (not to scale). Beam direction is from right to left, the total length is 100 m.

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 after the booster 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. After a collimation section, the beam 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 on the beam to drive a VUV free-electron laser demands a design of the injector which leads to high brilliance beams: high peak current, small transverse emittance in both planes and low energy spread – as listed in Table 1. To our knowledge, no injector has delivered a beam yet, which fulfilled all these required parameters at the same time. As an example, 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 of the TTF-FEL[5] 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. In the design, the bunch is then compressed to 0.8 mm (BC1) prior to acceleration to 150 MeV. A second compression to 250 μm (BC2) leads to the required peak current. The precompression to 0.8 mm is necessary to keep the energy spread required for lasing below 0.1 %. The design parameters are listed in Table 1: (a) for the initial TESLA 500 design as defined in [6], (b) a revised set close to the TESLA parameters from [7], and (c) the parameters for the TTF-FEL[5].

3. Optimized beam parameters for the FEL runs

As a matter of fact, the TTF injector has to fulfill various demands on beam properties, which are in conflict with an optimized design especially

Table 1. Injector design parameters for TESLA related experiments and TTF-FEL phase 1 operation. TTFL(a) is the initial TESLA 500 design, TTFL(b) a set close to the revised design. Note: the actual performance may differ from this table. Refer to the text.

<table>
<tr><th rowspan="2">Parameter</th><th rowspan="2"></th><th colspan="2">TTFL</th><th rowspan="2">FEL</th></tr>
<tr><th>(a)</th><th>(b)</th></tr>
<tr><td>RF frequency</td><td>GHz</td><td colspan="3">1.3</td></tr>
<tr><td>Repetition rate</td><td>Hz</td><td colspan="3">10</td></tr>
<tr><td>Pulse train length</td><td>μs</td><td colspan="3">800</td></tr>
<tr><td>Pulse train current</td><td>mA</td><td>8</td><td>9</td><td>9</td></tr>
<tr><td>Bunch frequency</td><td>MHz</td><td>1</td><td>2.25</td><td>9</td></tr>
<tr><td>Bunch charge</td><td>nC</td><td>8</td><td>4</td><td>1</td></tr>
<tr><td>Bunch length (rms)</td><td>mm</td><td>1</td><td>1</td><td>0.8</td></tr>
<tr><td>Emitt. norm. (x,y)</td><td>μm</td><td>20</td><td>10</td><td>2</td></tr>
<tr><td>ΔE/E (rms)</td><td>%</td><td colspan="3">0.1</td></tr>
<tr><td>ΔE/E (bunch to bunch) (rms)</td><td>%</td><td colspan="3">0.2</td></tr>
<tr><td>Injection energy</td><td>MeV</td><td colspan="3">20</td></tr>
<tr><td colspan="5">After 2nd compression</td></tr>
<tr><td>Bunch length (rms)</td><td>mm</td><td></td><td></td><td>0.25</td></tr>
<tr><td>Bunch current</td><td>kA</td><td></td><td></td><td>0.5</td></tr>
</table>

for an FEL. As an example, for the measurements of higher order modes in TESLA cavities, a 54 MHz bunch train has been produced, where the charge along the train could be modulated with frequencies between 0.3 and 27 MHz[10]. These beam parameters are substantially different to those required for FEL operation and nevertheless have to be realized as well.

A difficult problem is the bunch compression at 20 MeV with the first bunch compressor (BC1). It has been designed for TESLA related experiments and meets the specifications in terms of bunch length and transverse emittance as in Table 1(a)[6].

Looking at the FEL case, a compression down to 0.8 mm is feasible however, with an expense in transverse emittance: simulation and measurements indicate an increase in transverse emittance mainly due to space charge effects. Simulations of the compressor suffer from the complicated space charge effects and do not give reliable predictions of the emittance. Measurements have been performed at the FNAL/NICADD Photo-Injector, a twin of the TTF injector. The results are reported in [8].

Initially, parameters of the RF gun have been adjusted to minimize the transverse emittance for a charge of 1 nC. The forward RF power is maximized 3 MW, a compromise between highest field on the cathode and reliable operation. This leads to a gradient on the cathode of 41 MV/m.

Other parameters have been optimized: The phase of the gun RF in respect to the laser pulses (the launch phase) has been chosen to be 40°, the laser spot flat top 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[9]. The length of the photoinjector laser pulse is $\sigma_l = 7 \pm 1$ ps leading to an electron bunch length of $\sigma_z = 3.2 \pm 0.2$ mm[11]. The energy spread measured with the injector dipole is 22.1 ± 0.3 keV with a long tail induced by the acceleration process of the rather long bunch[1]. The energy spread measurement above is limited by the resolution of the optical system. An improved system is going to be set up soon.

The measured uncorrelated energy spread is well within the design, however, due to the long bunches from the RF gun, the RF induced correlation is large. Because of the predicted increase in transverse emittance by the low energy bunch compressor, we decided not to use the bunch compressor at low energy for the first tuning for FEL operation, only the second compressor at 150 MeV. With this compression scheme, we took advantage of the large correlated energy spread induced by the off crest acceleration. Off crest acceleration is required for magnetic chicane bunch compression. Because of the very small uncorrelated energy spread from the RF gun, its projection on the time/phase axis results in a high peak current spike with a long tail. This is illustrated in Fig. 2. It shows a simulation[12] of the longitudinal phase space performed with the beam parameters above and nominal compression settings for the second bunch compressor BC2, but with BC1 switched off. A bunch charge of 3 nC is used.

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. A high acceleration gradient on the cathode of 41 MV/m reduces space charge effects and improves further the peak current. 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. The launch phase has been slightly decreased from 40° closer to 30°.

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.

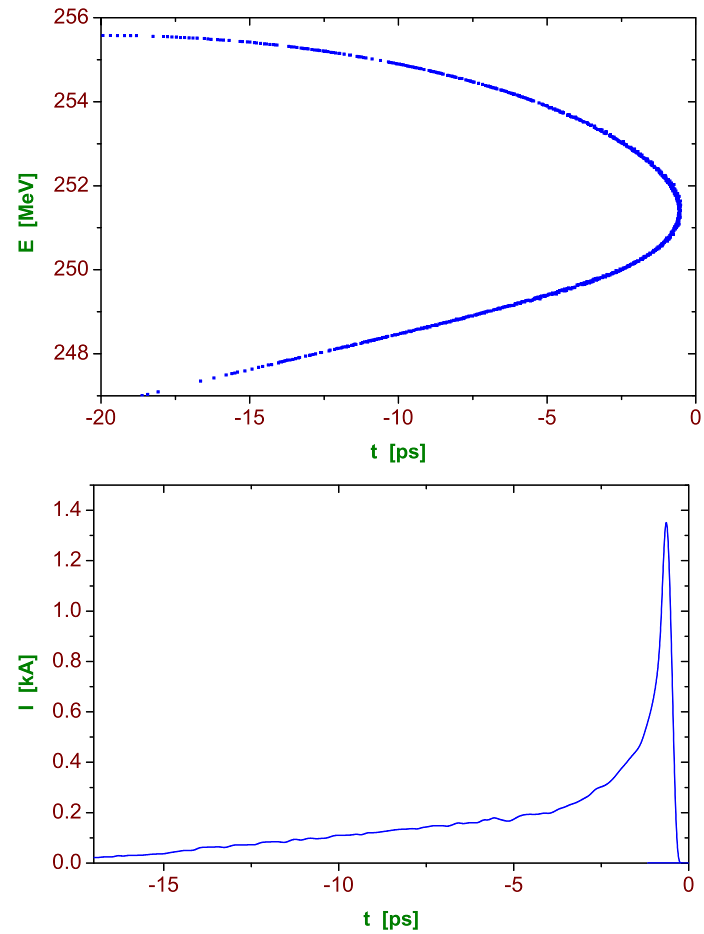

Figure 2. Simulation of the longitudinal phase space after bunch compression (upper) with its projection on the time axis (lower). Beam parameters of the improved operation mode used. Refer to the text for details.

4. Experimental set-up and results

4.1. *Transverse emittance*

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 $100\,\mu$m well within the resolution of $50\,\mu$m.

Downstream the booster we measure an emittance of 3.0 (3.2) $\pm$ 0.5 mm mrad horizontal (vertical). At 137 MeV we obtain a larger emittance of 8 (9) $\pm$ 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, bypassing BC1, but going through BC2 without compressing.

On full compression of the beam, for certain quadrupole settings, a break up of the transverse profile into two or three bunchlets is observed. This makes it difficult to give a meaningful emittance number. Simply projecting the total beam profile regardless of its internal 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 [9]), however, the break up into bunchlets is not yet fully understood.

The emittance data are projected emittances. A principle problem with projections is, that they do not take into account the internal structure of the beam. We know, that after full compression the beam is not gaussian shaped anymore, and that only the slice of the bunch contributes to the lasing process, which fulfills the requirement for peak current, emittance and energy spread. Since we cannot identify the slice which lases, we can only use the emittance numbers above as an upper estimate of the lasing slice emittance.

However, 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 (see Fig. 3). This estimate is in good agreement with the measurement in the injector. One would suggest, that after compression the beam keeps its injection emittance in its core, even if the projected full emittance is growing significantly.

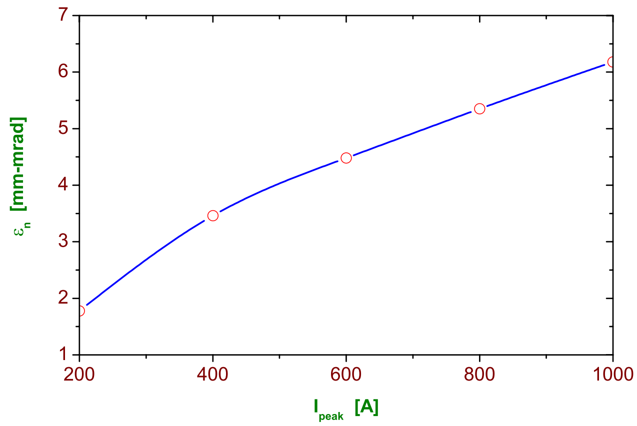

Figure 3. Estimated emittance of the lasing bunch slice for different peak currents of this slice, deduced from properties of the measured SASE radiation.

4.2. *Bunchlength*

For the bunch length measurements, we use synchrotron radiation emitted by the horizontally deflecting spectrometer dipole after the undulator (see Fig. 1). The optical part of the synchrotron radiation is guided by aluminum mirrors to a streak camera. It has an intrinsic resolution of 210 fs (FWHM)[13]. Details of the set-up are described in [11]. 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 4 (A) shows an overlay of several measurements of the same longitudinal bunch profile. The average profile is shown in Fig. 4 (B). The profile has a clear leading peak and a long tail. The width of the leading peak is 650 ± 100 fs (sigma).

With the high resolution camera we have been able to see substructures in the longitudinal beam profile. This has not been possible in earlier measurements, where only rms numbers of the width could be given[11]. The rms width of the data presented here is consistent with the previous measurements.

From the measured 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[14] is overlaid to the streak camera profile in Fig. 4 (B). The data of both methods agree very well, except that the tomographic data show a larger but shorter tail.

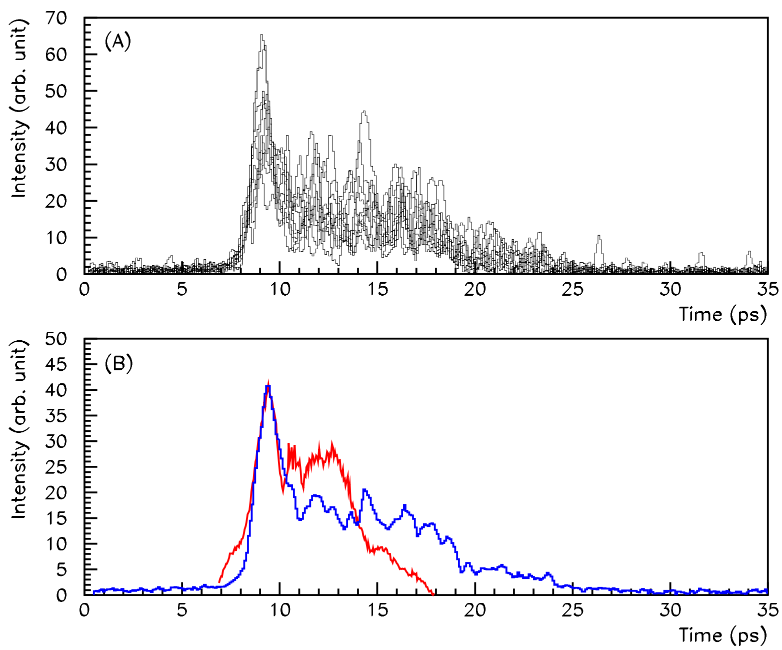

Figure 4. Several measurements of the same longitudinal beam profile obtained with a streak camera (A). The average over all profiles is plotted in (B), blue (long tail) curve. These data have been taken under beam conditions for lasing close to saturation. For comparison, a profile obtained with tomographic methods is overlaid in (B), red (short tail) curve.

Measurements have also been done with precompressed bunches using BC1. With a moderate compression down to 2 mm, the RF induced curvature in the longitudinal phase space is less pronounced and leads to a longer peak after the second compression stage closer to the design of 250 μm. The effect of lengthening or tailoring of the lasing bunch slice is clearly visible in the measured internal mode structure of the FEL radiation[15].

5. Discussion and Conclusion

To drive the TTF-FEL, the demands on both, the longitudinal and transverse phase space could not be fulfilled at the same time for the total bunch.

Full bunch compression in the injector at 20 MeV down to the design of 0.8 mm was not possible without spoiling the transverse emittance. The solution is to take advantage of the RF induced correlated energy spread 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 and energy spread small.

Acknowledgement

We like to thank our colleagues from INFN Frascati and Roma II for their support on the optical transition radiation devices.

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