THE INJECTOR OF THE VUV-FEL AT DESY

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Abstract

The VUV-FEL is a free electron laser user facility being commissioned at DESY in Hamburg. In the current configuration, the linac accelerates an electron beam up to 730 MeV. The injector is a crucial part of the linac, since it has to generate and maintain a high brightness electron beam required for SASE operation. The injector includes a laser driven RF gun, a booster section, a bunch compressor, and diagnostic sections. The good performance of the injector was crucial for the first lasing of the VUV-FEL at a wavelength of 32 nm in January 2005. We report on the present layout of the injector, the properties of the electron beam and on upgrade plans scheduled in the near future.

INTRODUCTION

For the VUV-FEL project at the TESLA Test Facility (TTF) at DESY, the properties of the electron beam are of prime importance. The first user facility for VUV and soft X-ray coherent light provides impressive peak and average brilliance. This is only possible with a beam perfectly matched to the requirements to drive the SASE process in a single pass high gain FEL.

The basic injector concept, a laser driven RF gun with a booster, has already been successfully used in the TTF phase 1 FEL providing beam until end 2002 for user experiments in the wavelength range of 80 to 120 nm.

Drawbacks of the first design motivated a redesign [1] to meet the demands for the goals of phase 2, the lasing down to a wavelength of 6 nm. There are two major changes in the design: the booster is extended so that an energy of more than 100 MeV is reached, and a third harmonic cavity is included to correct non-linearities in the phase-energy phase space. In addition, a extended diagnostic section after the first bunch compressor has been included. The installation of the new injector has been completed in February 2004, with the exception of the third harmonic cavity. Its installation is forseen in 2006.

The development of major components like the laser system, the RF gun, and the cathodes are performed at the photoinjector test facility PITZ. The advantage is, that well understood equipment is installed at the VUV-FEL and further R&D does not hamper the VUV-FEL runs.

The RF gun system has been commissioned at PITZ where with a full characterization of the system, an optimal working point for smallest transverse emittance has been determined [2, 3]. After the installation at TTF, only the solenoid current had to be slightly adjusted to match the beam into the booster section.

With the well commissioned injector, first lasing at a wavelength of 32 nm has been achieved in January 2005. See [4] and [5] for details.

THE INJECTOR CONCEPT

Figure 1 gives a schematic overview of the present configuration, Fig. 2 shows a view from the RF gun down the accelerator. Table 1 summarizes main parameters.

The injector is based on a laser-driven photocathode RF gun and a booster section. The main goal is to achieve a transverse emittance smaller than 2 mm mrad for a charge of 1 nC. The working point is chosen such, that space charge induced emittance growth is as much reduced as possible. The RF gun design realizes a perfect symmetric field to reduce RF induced emittance growth. Since the transverse emittance scales with the laser spot size on the cathode, the reduction of space charge is realized choosing an initially long bunch (2 mm). The matching into the booster and the choice of accelerating gradients are such, that the transverse emittance is not only kept small, but is also damped to some extend (see [6] for details).

The bunch is compressed using magnetic chicane bunch compressors. The peak current of the uncompressed bunch of about 70 A is increased to more than 2 kA. The compression requires an energy chirp along the bunch which is generated by off crest acceleration. The compression is

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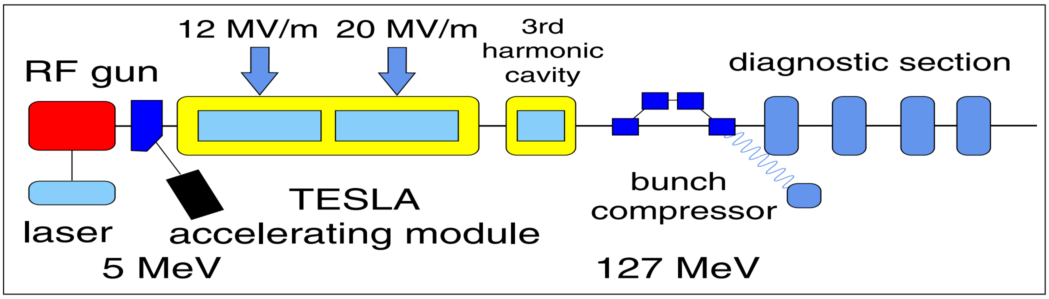

Figure 1: Schematic overview of the TTF VUV-FEL injector (not to scale). Beam direction is from left to right, the total length is 30 m. The third harmonic cavity is not installed yet.

Table 1: Present operating parameters of the VUV-FEL injector at start-up.

RF frequency	GHz	1.3
Energy	MeV	127
Bunch charge	nC	0.5 - 1.0
Nb. of bunches/train		30
Bunch train length	ms	0.03
Rep. rate	Hz	2
Laser spot size (rms)	mm	0.6
RF gun phase*	$^\circ$	38
Acc. module phase**	$^\circ$	-8
Emittance, norm. (x,y)	μm rad	1.4
Bunch length (rms, uncompressed)	mm	1.7
Spike length (rms, compressed)	μm	50
Uncorrelated energy spread	keV	< 25
ΔE/E (rms)	%	0.02

* in respect to zero crossing
** in respect to on crest

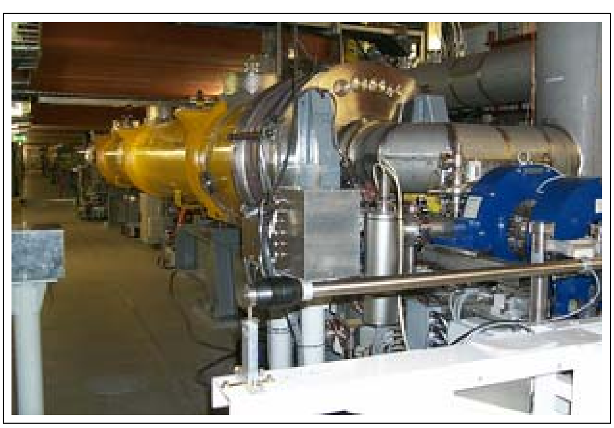

Figure 2: View of the VUV-FEL injector from the RF gun down the accelerator. The RF gun is inside the blue solenoids in the foreground. The yellow cryostat is the TESLA module used as a booster.

done in two steps at energies of 127 MeV and 370 MeV in order to avoid an unacceptable emittance growth due to space charge, wakefield, and coherent synchrotron radiation effects.

Accelerating a bunch which is long in respect to the RF wavelength (a few degrees of RF phase) leads to a curvature in the energy-phase plane. This curvature can be removed by a third harmonic cavity following the accelerating section. A superconducting third harmonic cavity is under construction [7]. For the start-up phase, emphasis is on lasing at 30 nm which can be obtained similar to TTF1 by tailoring the longitudinal structure of the electron beam to produce a spike with the required peak current. See [8] for details.

THE RF GUN AND BOOSTER

The RF gun is a 1.5 cell L-band cavity (1.3 GHz, TM_{010} mode) powered by a 5 MW klystron. To keep a perfect symmetry of the RF field, the gun is equipped with a longitudinal RF coupler. Moreover, it has no probes or tuning paddles which may distort the RF field. The gun is tuned by fine adjusting its temperature. The water cooling system is able to cope with an average RF power of 50 kW. During operation when the load on the gun is constant, the cooling system stabilizes the temperature to 0.05°C.

The RF gun is operated with a forward power of 3.1 MW yielding an accelerating field on the cathode of 41 MV/m. During the start-up phase of the VUV-FEL where a high repetition rate and long bunch trains are not required, the gun is operated at 2 Hz and an RF pulse length of 100 μs. During the commissioning at PITZ and TTF [9], the gun has been operated up to 10 Hz with an RF power of 3 MW and an RF pulse length of up to 0.9 ms (27 kW average power).

The forward and reflected power is measured with a DSP based system enabling a low level control of the RF power. The forward power is stabilized to 0.1 % (rms), the phase stability achieved is better than 0.5 °(rms).

We use a Cs_2Te photocathode which is inserted via a load-lock system to the back of the half cell. The quantum efficiency of the cathodes is initially high (in the order of 5-9 %) [10] and decreases slowly over several month to about 1 %.

A solenoid (0.163 T) focuses and matches the beam to the booster section. A bucking coil compensates the remnant magnetic field on the cathode surface to zero.

The booster accelerates the beam to 127 MeV. It is a TESLA module with eight 9-cell superconducting 1.3 GHz cavities. To avoid strong transverse focusing, the gradient of the first four cavities is chosen with 12 MV/m moderate. It is the optimum according to the emittance damping scheme. The last four cavities are operated with higher gradients, 19 MV/m in average. The module is powered by one 5 MW klystron. The RF power is split with a hybrid/phase-shifter combination.

THE LASER SYSTEM

The laser is based on a Nd:YLF mode-locked pulse train oscillator synchronized to the 1.3 GHz RF of the accelerator. The diode pumped pulse train oscillator is operated at 27 MHz. Pockels cell based pulse pickers running at 1 MHz prepare the pulse train required for the VUV-FEL operation. The system is designed to produce pulse trains with up to 800 μs length. The pulse spacing is usually 1 μs (1 MHz), a 9 MHz mode is in preparation. The pulse train is amplified with a linear chain of amplifiers, two stages are pumped with laser diodes [11], the last two with flashlamps. A system entirely pumped with laser diodes has been set-up and is being commissioned at PITZ.

The infrared wavelength of the laser is converted into the UV (262 nm) with two non-linear crystals (LBO and BBO). The beam is transported to the RF gun with an imaging system. Movable mirrors allow to control the position of the laser spot on the cathode. The last mirror is mounted in a vacuum chamber close to the gun and reflects the beam onto the cathode under a small angle (1.7°). To avoid charging up, and to avoid wakefield effects on the electron beam, the mirror is fabricated out of pure aluminum.

The temperature in the laser room is stabilized to 0.1 °C to reduce drifts as much as possible. The rms charge fluctuation measured after the RF gun is 2 % shot to shot, averaged over the pulse train 1 % (rms). The longitudinal pulse shape is gaussian, the pulses length measured with a streak camera is $\sigma_{\mathrm{L}} = 4.4 \pm 0.1$ ps (at 262 nm). The transverse laser pulse shape has a clipped gaussian shape with an homogeneity of about 20 %. Techniques to produce flat-hat transverse and longitudinal shapes with improved homogeneity are under development at PITZ [12].

MEASUREMENT OF BASIC BEAM PARAMETERS

Energy and Energy Spread

Directly after the RF gun, the beam momentum is measured in a dispersive section. The measured beam momentum as a function of the accelerating RF field in the gun agrees well with the expectation from simulations. For instance, for an RF power of 3 MW the momentum amounts to 4.7 MeV/c. After acceleration to 127 MeV, the energy and energy spread are measured in the dispersive section of the first bunch compressor using a view screen (optical transition radiation). Due to the initial long bunch length of 1.7 mm, the beam shows a sharp core and a long energy tail. The width of the core is smaller than 25 keV (rms) and is a good estimate of the uncorrelated energy spread. A small uncorrelated energy spread is important for the development of a sharp temporal spike after the compression stage. The correlated energy spread could not be measured at the RF gun. Since the phase for minimum energy spread after acceleration in the booster is only 2° in phase away from the maximum energy gain, we conclude that the correlated energy spread is small.

With the low level RF feedback system regulating the phase and amplitude of the accelerating structures, the energy stability is measured to be $dE/E = 2.6{\cdot}10^{-4}$ (rms). We also see drifts of the energy in the order of 0.08 %. These drifts are mainly due to temperature drifts in the electronics and cables. An improvement of the temperature stabilization is in preparation.

Emittance

The emittance is evaluated from the beam sizes measured on four screens embedded in a FODO lattice. Digital CCD cameras record the optical transition radiation generated by the electron beam on the screens (silicon wavers with an Al coating). The resolution achieved is 10 μm [13].

Fig. 3 shows the horizontal and vertical normalized transverse rms emittance measured at 127 MeV for a bunch charge of 1 nC repeated several times within 75 min. Two different methods are used to calculate the emittance (see [14] for details). The true rms emittance is calculated from the full and from 90 % of the intensity. A tomographic technique is also applied, which reconstructs the phase space. The tomographic method agrees well with the pure rms calculation.

In the example shown, the 90 % rms emittance 1.6 mm mrad. The data also show, that the emittance is maintained stable over a long time period, actually much longer then the measurement period in this example. Retuning of the injector is required only after major shutdowns. The rms fluctuation of the emittance is about 2 to 3 %. This corresponds to the statistical error of the measurements. The systematic error is estimated with 6 % mainly due to calibration error of the quadrupole fields and the uncertainty of the beam energy. With more data collected over the last months of running time, the geometrical average of the horizontal and vertical emittance is 1.4 mm mrad [15], with the measurement errors given above.

Bunchlength

The uncompressed bunch is measured with a streak camera (Hamamatsu FESCA-200) using synchrotron radiation emitted by the last magnet of the first bunch compressor at 127 MeV. The length is 1.7 ± 0.2 mm (rms) as expected. In the case of fully compression, the leading spike is expected to have a width in the order of 100 fs. Being close

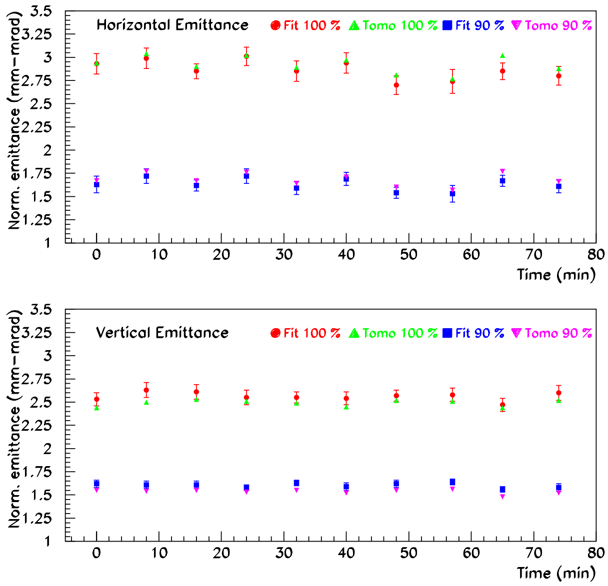

Figure 3: Transverse rms emittance measured at 127 MeV for a bunch charge of 1 nC repeated several times within 75 min.[13] Horizontal and vertical projected emittances are shown analyzed with two different methods (see [14] for details): the true rms calculated from the full and from 90 % of the intensity, and calculated using a tomographic technique.

to the resolution of the camera (100 fs rms), wavelength filters are required to reduce dispersion effects which reduce the number of photons reaching the camera. Currently, we work on the improvement of the photon yield of the synchrotron radiation beamline.

A deflecting cavity [16] is used after acceleration at 445 MeV to streak the electron beam. The streaked beam is measured with a view screen. The deflecting cavity provides a better signal to noise ratio and a better resolution of 10 to 50 fs (depending on the focusing of the beam). The compressed bunch shows the expected longitudinal bunch structure: a leading spike with a width of 120 fs (fwhm) and a long tail of 2 ps. See [17] for details.

The deflecting cavity has also been used to measure the emittance of a longitudinal slice of the beam. The data are still preliminary, They indicate, that the emittance is constant along the tail and increases at the high current spike.

Additional methods to measure the bunch length with interferometers and electro-optical sampling techniques are described in [18, 19].

CONCLUSION

The injector of the VUV-FEL has been successfully commissioned in 2004 and brought into operation summer 2004. The projected beam parameters are well understood, a good working point in terms of small emittance and short bunches has been established. First measurements of the temporal structure after compression and the slice emittance have been started. The excellent performance of the injector have been the bases for the first lasing at a wavelength of 32 nm.

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