BEAM DIAGNOSTICS AT THE VUV-FEL FACILITY

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Abstract

The free electron laser (FEL) at the TESLA Test facility at DESY, now called VUV-FEL, will be the first FEL user facility for VUV and soft X-ray radiation down to 6 nm wavelength, the commissioning starts in summer 2004. Commissioning as well as stable FEL operation require a combination of different diagnostic tools for measuring both electron and photon beam parameters, including the full phase space distribution of the bunch charge, exact timing with sub-picosecond resolution, electron and photon beam overlap along the undulator, radiation beam position in the user area 50-70 m behind the undulator, intensity and spectral distribution of the radiation pulses and others. This contribution gives an overview of the electron and photon beam diagnostics of the FEL facility and focuses particularly on the instrumentation which is crucial or specific for the FEL operation.

INTRODUCTION

During the past 10 years, the TESLA Collaboration has established the TESLA Test Facility (TTF) on the DESY site in order to develop the technology for a superconducting linear electron-positron collider and a X-ray free electron laser facility. The first phase of this project, TTF1, was successfully completed in 2002 with an extended operation period for first scientific applications of the saturated FEL beam below 100 nm wavelength [1], the shortest wavelength ever reached by a single-pass SASE (self-amplified spontaneous emission) FEL [2].

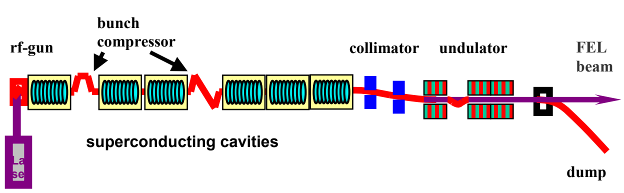

Figure 1: Schematic layout of TTF2.

Convinced of the unique possibilities provided by this new kind of radiation source, DESY is now completing the VUV-FEL user facility which makes use of the upgraded TTF accelerator (TTF2) [3]. The layout of TTF2 is schematically shown in Figure 1. It consists of a photocathode RF gun and five superconducting accelerator modules of the TESLA type (cryo-modules) each containing 8 L-band 9-cell cavities. A sixth module will be added later to reach the full design energy of 1 GeV, corresponding to 6.4 nm wavelength of the FEL. Two bunch compressors will be used to compress the electron bunches down to the 30 µm regime in order to produce kA peak currents at low emittance (below 2 mm mrad). The linear accelerator (LINAC) is followed by a collimation section, acting in all 6 phase space dimensions, in order to avoid losses of beam halos in the 30 m long hybrid FEL undulator. The FEL radiation produced by the undulator will be transported to a separate hall where carbon coated, plane mirrors at grazing incidence angles are used to steer and focus the radiation into one out of five experimental stations. The layout of the experimental floor is shown in Figure 2. An optical laser system synchronised with the FEL has been built and installed near the user experiments in order to exploit the ultra-short FEL pulses for the study of chemical reactions and other fast phenomena on a sub-picosecond time scale.

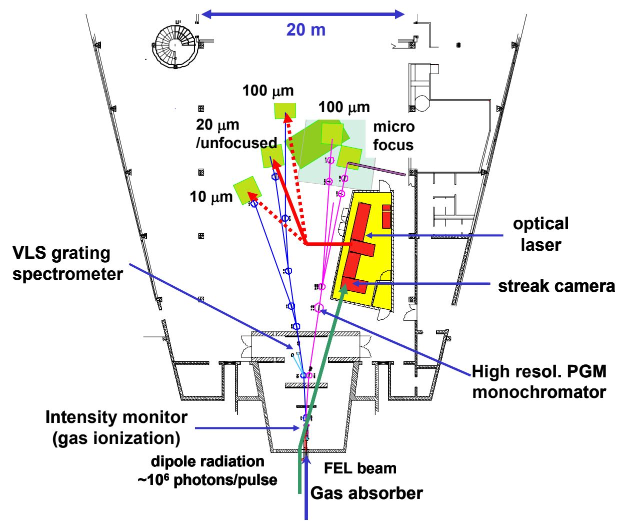

Figure 2: Layout of the experimental area of the VUV-FEL.

The photoinjector with the first accelerator module has already been commissioned in spring 2004. After final installations in summer, the commissioning of the accelerator and the FEL is planned for the second half of 2004. It is expected that first user experiments can be started in spring 2005.

The superconducting RF technology of the linac allows to deliver up to 7200 bunches in 800 µs long bunch trains at a repetition rate of 10 Hz. This feature together with fast beam switching techniques will allow in the future providing radiation pulses in a very flexible way for many user experiments working quasi-simultaneously. The European XFEL project is based on the same technology, thus the operation and consequent improvement of the VUV-FEL will be essential for the success of the XFEL and other FEL facilities proposed in Europe.

DIAGNOSTICS REQUIREMENTS

In contrast to 3rd generation synchrotron light sources the next generation FEL sources are single pass devices based on pulsed accelerators. Furthermore, due to the nonlinear and stochastic FEL process, the accelerator, the electron beam parameters along the FEL undulator, the beamlines and experiments are now strongly coupled. Consequently, event oriented data acquisition systems have to be used for both machine operation and user experiments, similar to high energy physics experiments. New measurement techniques have to be developed for diagnostics and experiments. Single bunch or single pulse resolution is required for a large set of parameters, such as beam position and charge along the entire machine, FEL pulse intensity, wavelength and pulse arrival time.

The various diagnostic systems may be arranged in three subgroups:

(1) Electron beam diagnostics to operate the machine

- Standard instrumentation is required to measure electron beam orbit, bunch charge, beam size, beam phase, energy and energy spread. In order to maintain reproducible settings of the machine for reliable FEL operation for user experiments, the electron beam orbit has to be measured and corrected to a precision of about 10 µm in the undulator region. The energy has to be controlled at least to the 10^{-4} level; this requires measuring the beam phase with an accuracy of < 0.1°.
- Fast protection systems with a response time in the µs range are required to shut off the beam in case of high losses. Such systems are essential for superconducting LINACs due to the large amount of transported energy. High losses at single points cannot only damage the undulator, but could also produce holes in the vacuum system.

(2) Diagnostics needed to control and optimize the FEL

In order to control and optimize the FEL process the phase space of both electrons and photons has to be measured and controlled. This includes not only the transverse emittance, but also the bunch length, its shape, energy and energy spread.

- The beam size has to be measured at different positions along the machine using screens and wire scanners with a resolution of 10 µm or even better.
- The bunch length and the longitudinal profile have to be measured at least to the 30 µm or 100 fs level. As shown in Figure 3 it is not sufficient to measure only the first moment of the charge distribution. Since there are no established techniques for this kind of precision, several different methods will be used and further developed.
- Similarly, a complete characterisation of the electron phase space distribution with a longitudinal resolution less than the radiation pulse length is required – it is the slice emittance and the slice energy spread that determine the FEL performance. Since the precise measurement of the first moments of the phase space distribution is already a complicated task, suitable techniques to measure slice parameters are currently all R&D projects in their own. An attempt using a transverse mode cavity is described below.
- For the optimisation of the SASE process in the FEL an online signal is required that allows setting the optimum phase for bunch compression with a precision of about 0.1°. A qualitative measurement of the coherent synchrotron radiation produced in the bunch compressor using simple infrared (IR) detectors is sufficient, fine tuning requires photon diagnostics (see below).

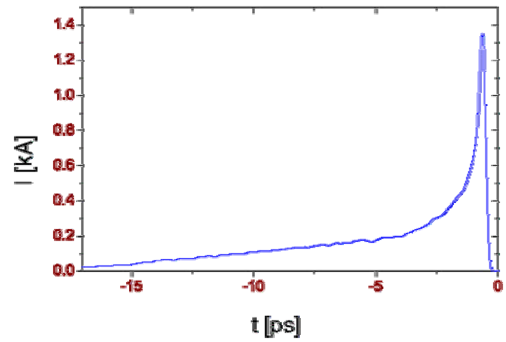

Figure 3: The electron distribution within a bunch simulated for TTF1. Lasing is supported only by the small fraction of the charge in the narrow spike produced by the bunch compressor [2].

(3) Diagnostics needed for user experiments

The FEL is a pulsed radiation source, the SASE process starts from noise such that every pulse is different, and virtually all user experiments will be pulse-resolved. Therefore, all relevant photon beam parameters must be measured and made available for the experimenter online, pulse resolved and for all pulses within a pulse train. They are also used for optimizing and controlling the FEL process.

- The basic characterisation includes the radiation pulse energy and the spectral distribution. Standard methods have been adapted and will be available.
- Time-resolved experiments need also information on the duration and the temporal structure of the radiation pulse. In addition the exact arrival time has to be measured, normally with respect to an optical femtosecond laser pulse when pump-probe techniques are used. No standard diagnostics with sufficient resolution are available at the present time; various methods are currently in the development phase such as electro-optical sampling (EOS) and correlation techniques. Accurate timing measurements will also be essential to reduce the arrival time jitter coming from bunch energy variations due to different path lengths through the bunch compressor chicanes.

DIAGNOSTICS FOR OPERATING THE LINAC

Standard Electron Beam Diagnostics

The standard diagnostics includes the usual monitor systems required for the operation of an accelerator. With the exception of cold beam position monitors (BPMs) in the cryo-modules these systems are concentrated in the warm sections of the LINAC. There are approximately 60 BPMs with a single-bunch resolution of < 30 µm in the beam line and < 10 µm in the undulator, 11 toroids for charge measurement, mainly one at the beginning and at the end of each warm section. 28 OTR-screens and 15 wire scanners are available to measure the beam size [4].

Since the emittance is mainly generated in the injector there is an emittance measurement section included at the end of the injector, formed by a FODO lattice with four OTR/wire-scanner combinations in the drifts [5]. This section allows to fix and to match the beam parameters between injector and main LINAC. The design of this station allows having the screen and the wire almost at the same place.

Since phase stability is crucial for timing and synchronisation of the FEL pulses, a new monitor providing fast beam signals has been developed (Figure 4). It consists of an isolated ring electrode terminated by 50 Ω, providing a bandwidth of about 10 GHz. A special electronics compares the phase monitor signal with the master frequency to detect the beam phase. The fast signal can also be used for triggering and timing purposes.

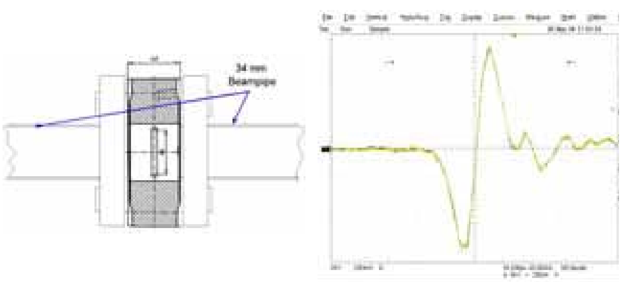

Figure 4: The TTF2 phase monitor (left), constructed as a thick, double-sided flange (40 mm) between two beam tubes. The signal of this monitor (right) was measured with a scope with 10 GHz analogue bandwidth.

Additional developments are ongoing in collaboration with CEA Saclay: A new BPM to be used in the cryo-modules and a dark current monitor to measure the dark current emitted by the gun into each 1.3 GHz bucket. Both monitors are based on the re-entrant cavity principle, which was used successfully during TTF1 for position and dark current measurements.

Protection Systems

Due to the large amount of energy transported within a superconducting LINAC effective protection systems are required to protect sensitive components. For instance a loss level of no larger than 10^{-7} is required in the undulator region in order to avoid demagnetisation. This is achieved by a combination of collimation and protection systems stopping the beam within 3 µs. For TTF2 a combination of two protection systems is used; one is based on beam transmission measurement using several toroid pairs [4], the second system is a network of 64 fast beam loss monitors distributed at sensitive positions along the accelerator. Alarms from these systems are collected in a fast distributed beam interlock concentration system and stop the drive laser of the gun within 3 µs. This time is mainly given by the signal travelling in the cables and the number of bunches that are already in the machine at the time of the alarm.

LONGITUDINAL DIAGNOSTICS FOR CONTROLLING THE FEL PROCESS

Coherent FIR Radiation

Synchrotron radiation generated in the dipole magnets of the first bunch compressor is transported by mirrors to a diagnostic container outside the accelerator tunnel. A 90° off-axis paraboloid mirror of 100 mm projected diameter and 810 mm focal length is mounted close to the z-cut crystalline quartz view port, reflecting radiation upward to the tunnel ceiling from where it is reflected out of the tunnel by a flat mirror of 250 mm diameter. The interferometer and the beamline are flushed with dry nitrogen to reduce the strong absorption of water vapour in the IR. This station is equipped with a 200 fs single shot streak camera using the optical part and a Martin-Puplett interferometer for the far-infrared (FIR) component (50 µm – 3 mm wavelength) of the radiation.

The bunch length measurement using FIR radiation relies on the modification of the synchrotron radiation spectrum at wavelengths comparable to the bunch length. Precise measurement of the spectrum allows either comparison with simulations for expected bunch shapes or, through the mathematical technique of Kramers-Kronig analysis, the independent reconstruction of the bunch profile [6].

Figure 5: Two views of the beamline for FIR and optical radiation installed at the bunch compressor.

Electro-optical Sampling

In the electro-optic sampling (EOS) method the optical anisotropy of a ZnTe crystal, induced by the electric field of the relativistic electron bunch and sampled with a 15 fs titanium-sapphire laser pulse, is used for non intercepting bunch length diagnostics.

Simultaneously with the electric field of the electron bunch a linearly polarized laser pulse is sent through the crystal. Due to the field of the bunch it becomes birefringent and thereby changes the polarisation state of the laser pulse. A λ/4 plate and a Wollaston prism separate the laser pulse into its two polarization components which are measured by a balanced receiver (Figure 6).

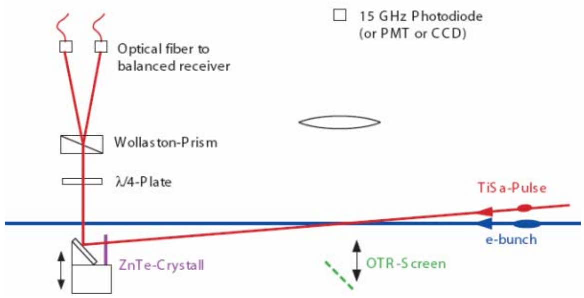

Figure 6: Principle of the EOS experiment.

The field is either sampled directly by varying the delay between electron bunch and laser pulse, or by coding time into the frequency spectrum of the laser and so shifting time information into the frequency regime [7] (Figure 7).

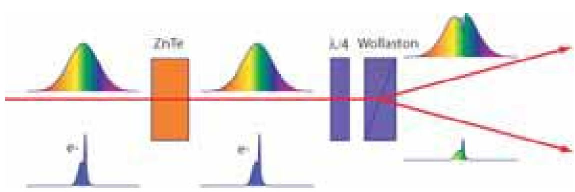

Figure 7: Principle of the time-to-frequency conversion.

The first approach requires precise synchronisation between the 1.3 GHz LINAC RF and the 81 MHz repetiton rate of the laser and is therefore rather sensitive to timing jitter. The second method is much less sensitive to jitter because the chirped pulse is longer than the bunch length and the complete spectrum is measured in a single shot.

Compression Monitor

The current state of the art of bunch length measurements is far from delivering an online signal on a bunch to bunch basis, or even with the repetition rate of the LINAC, that could be used to set up, optimize and stabilize the machine for stable SASE operation. However, it is usually sufficient to see trends in the bunch length, or to have an indication when the shortest possible bunch is reached. Coherent radiation in the FIR produced in bends or by screens can provide such a signal. As soon as the bunch length is shorter than a certain wavelength, the particles emit coherently in this part of the spectrum and the intensity rises steeply. This change of intensity in a certain spectral range can be observed with a simple FIR detector. Figure 8 shows the intensity variation behind the TTF2 bunch compressor with the phase of the preceding RF cavities measured with different detectors during the recent injector commissioning. Using sufficiently fast detectors together with some additional spectral filtering and normalisation it is even possible to supply a fast feedback signal for the RF phase regulation on a bunch-to-bunch basis in order to keep the compression on the maximum value.

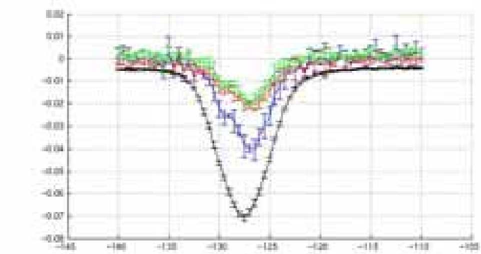

Figure 8: Variation of the FIR intensity with the RF phase of the acceleration structure measured with different detectors in the TTF2 bunch compressor.

Transverse Mode Cavity

A standard tool to measure ultra-fast processes is the streak camera. This principle has also been used for the diagnostics of relativistic electron beams by deflecting the electron bunches by a transverse mode cavity [8]. The concept is schematically shown in Figure 9. In addition to the bunch length this method gives also access to slice parameters of the electron bunch, at least in one transverse direction. Using a horizontal kicker, in combination with the vertical deflection by the cavity, one can select bunches from a long bunch train, and observe them on an off-axis screen. In collaboration with SLAC, Stanford, such a system has been installed at TTF2 and will be commissioned in fall 2004.

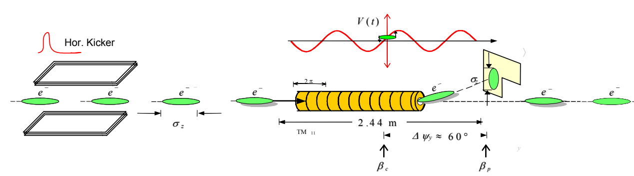

Figure 9: Scheme of electron bunch streaking by a transverse mode cavity.

PHOTON DIAGNOSTICS

Radiation Pulse Energy and Beam Position

The radiation pulse energy is the most important photon beam parameter needed online for every experiment as well as for controlling the FEL process. A new detector has been developed for this purpose which is based on the photoionisation of a rare gas at low density. The device is indestructible and almost transparent. It has been tested successfully at TTF1 to monitor the intense VUV FEL pulses at 87 nm wavelength [9]. The principle design is shown in Figure 10. The dynamic range of the detector is extremely large and allows its accurate absolute calibration using spectrally dispersed synchrotron radiation at much lower photon intensities. The new detector unit for the VUV-FEL has been constructed and calibrated by the PTB, Berlin, and will be installed at the entrance of the experimental hall (see Figure 2). It will be complemented by two further units which are equipped with split electrodes such that also the photon beam position can be monitored with high precision.

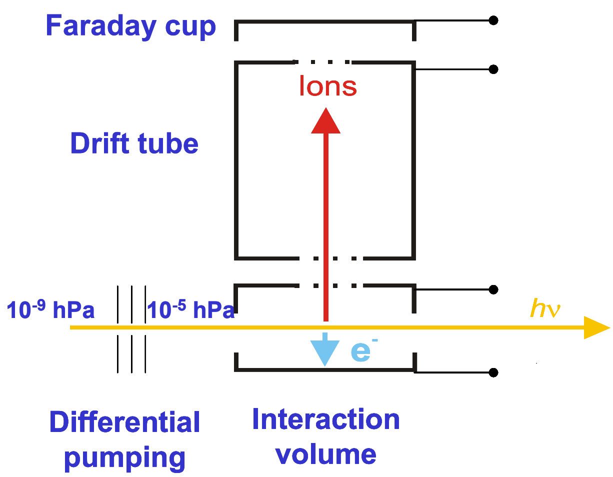

Figure 10: Gas ionisation detector to monitor the radiation pulse energy.

On-line Spectra of Single FEL Pulses

Many user experiments are sensitive to the detailed spectral distribution of the radiation pulse but do not need or like to use a narrow-band monochromator. We have therefore developed an online spectrometer based on a varied line-spacing plane grating (Figure 11) [10]. The grating reflects approximately 90 % of the radiation in 0^{th} order to the experiment while a small fraction is dispersed and focused on a screen or linear detector such that the complete spectrum can be measured for a single pulse. The spectrometer will be installed in the left beamline branch behind the gas monitor (see Figure 2) such that it can be used by three experimental stations.

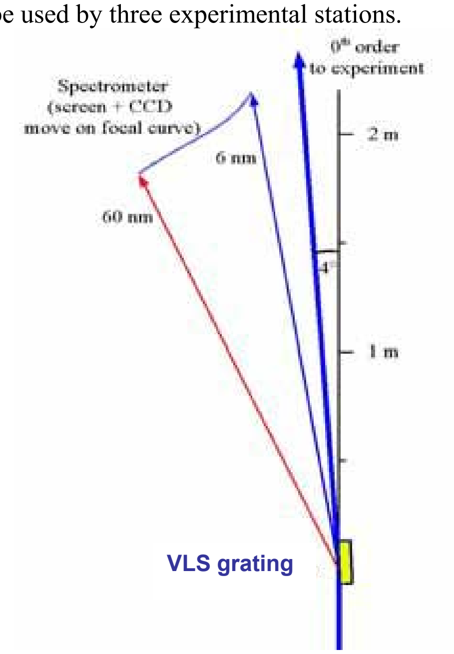

Figure 11: Scheme of the VLS grating spectrometer for the online measurement of single pulse radiation spectra.

Synchronisation and Temporal Structure

Different photon diagnostics needed for synchronising an optical femtosecond laser with the FEL on the 100 fs level is currently under development. In this time domain correlation techniques are normally used where two light pulses are overlaid in a non-linear crystal or another medium. These standard techniques will be tested on the VUV-FEL by combining the optical laser and visible synchrotron radiation (SR) which is produced by the same electron bunch that generated the FEL pulse. In addition, the optical laser pulse and the SR pulse will also be focused on a streak camera such that the delay between the two can be measured directly.

Another development project is a single-shot correlator combining FEL and optical laser pulse. This device is based on changes in the photoionisation spectra of rare gas atoms in the presence of a strong laser field. It has become a standard technique for the characterisation of ultra-short VUV and soft X-ray pulses produced by high-harmonic generation [11].

Furthermore, a special electro-optical system for high resolution arrival time measurement is currently under construction at the VUV-FEL [12]. This system uses a fraction of the pump-probe laser pulse transported to the electron beam through a 170 m long optical fibre.

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