# ELECTRON BEAM CHARACTERIZATION AT PITZ AND THE VUV-FEL AT DESY

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*Abstract*

The VUV-FEL at DESY Hamburg is a user facility for SASE FEL radiation in the VUV wavelength range. The quality of the high brightness electron beam driving the VUV-FEL plays an important role for the performance of the facility. Prior to installation, the VUV-FEL electron RF gun has been fully optimized and characterized at the PITZ photoinjector test facility at DESY, Zeuthen, dedicated to develop high brightness electron sources for FEL projects like the VUV-FEL and the XFEL. We summarize here the results of transverse emittance optimization at PITZ and report on the upgrade of the PITZ facility presently under construction. At the VUV-FEL normalized projected transverse emittances around 1.4 mm mrad for 90% of a 1 nC bunch have been regularly measured. These emittance measurements are described here, as well as recent measurements of the longitudinal bunch profile using a transverse deflecting cavity.

## INTRODUCTION

The VUV-FEL [1], a SASE FEL user facility at DESY (Hamburg) operating in the wavelength range from vacuum ultraviolet to soft x-rays, has been commissioned during 2004 and in the beginning of 2005. The first lasing, at the wavelength of 32 nm, was achieved in January 2005 [2, 3], and the first user experiments started in summer 2005. Besides providing FEL radiation for the FEL studies and experiments, the VUV-FEL is a piloting project of the European X-Ray Free Electron Laser Facility (XFEL) [4]. The electron linac driving the VUV-FEL is used also as a test bench for the International Linear Collider (ILC) [5].

The RF gun of the VUV-FEL has been optimized and characterized, prior its installation to the VUV-FEL accelerator tunnel in January 2004, at the PITZ photoinjector test facility at DESY, Zeuthen [6]. The PITZ facility has operated since 2002 as a test bench for the development of high brightness electron sources for FEL projects, and it is presently being upgraded to an electron beam energy up to 30 MeV.

The FEL process demands a bunched electron beam with a high peak current, a small transverse emittance, a small momentum spread, and a short bunch length. In order to achieve these high demands, accurate characterization of the electron beam is necessary. We summarize here measurements and optimization of the transverse emittance at PITZ and at the VUV-FEL. Measurements of the longitudinal phase space at PITZ are shortly described as well as the longitudinal bunch structure measurements at the VUV-FEL using a transverse deflecting cavity.

## PHOTOINJECTOR CONCEPT

The injector is a key element of a linear accelerator producing high brightness electron beams. The photoinjector consists of a laser driven RF gun with solenoid magnets, a booster cavity, and magnetic bunch compressors. In order to suppress the space charge induced emittance growth, a homogeneous transverse and longitudinal distribution of the laser pulse is desired. For the same reason, the accelerating field on the photocathode is as high as possible. The solenoid magnet located close to the photocathode is used to counteract the space charge induced emittance growth. It also contributes to a reduction of the correlated emittance via a so-called emittance compensation process [7]. A second solenoid (the bucking coil) is used to compensate the magnetic field on the photocathode to zero. In order to reduce the space charge induced emittance growth, a matching technique based on the so-called “invariant envelope” [8] is used: The beam should be at a waist on the entrance of the booster, and the energy gain of the booster should be selected correctly according to the beam size, the incoming beam energy, and the peak current. More details of this matching scheme is in [9].

The high peak current required for the FEL process is achieved by compressing the electron bunch. Typically a magnetic chicane bunch compressor downstream of a

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booster cavity is used. A sinusoidal accelerating field of the booster cavity induces a curvature in the longitudinal phase space. Thus, the compression of an off-crest accelerated bunch leads to a longitudinal bunch structure with a high peak current spike and a long tail. The energy-phase plane curvature can be removed by using a superconducting third harmonic cavity (3.9 GHz) [10] before the bunch compressor. The third harmonic cavity of the VUV-FEL is still under construction, and therefore the start-up lasing strategy of the VUV-FEL is similar than at the TTF-FEL [11]: A spike is used to produce the required peak current.

## PITZ

The PITZ facility has been built to develop and optimize high brightness electron sources for FEL projects. The first stage of the facility (PITZ 1) consisted of a laser system providing long trains of short, spatially and temporally homogeneous UV pulses, a 1.5 cell RF gun (1.3 GHz) with a $Cs_2Te$ photocathode, a solenoid system to compensate space charge induced emittance growth, and a diagnostic section for measurements of transverse emittance, bunch length, momentum, and momentum spread. Electron beam momentum of 4.7 MeV/c is reached when operating the RF gun with an input power of 3.3 MW. Since 2004 it is possible to operate the gun with a higher power resulting in an increased beam momentum (up to 5.2 MeV/c). The nominal bunch charge is 1 nC. A schematic overview of the PITZ 1 facility is shown in Fig. 1.

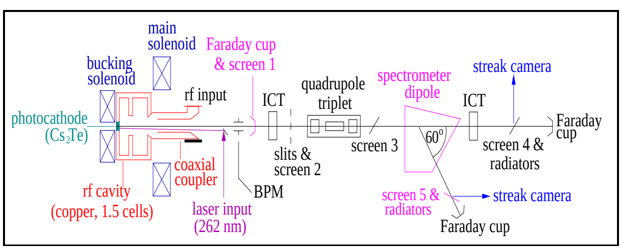


Figure 1: Schematic overview of PITZ 1. Beam direction is from left to right, and the total length is about 6 m.

In the following we concentrate on the optimization of the transverse emittance. Other results and more details of the PITZ facility are in [6, 12, 13, 14, 15].

### *Emittance optimization*

The transverse projected emittance at PITZ is measured using a single slit technique. The advantage of the slit technique is that the space charge effects, which otherwise need to be taken into account at low electron beam energies, are strongly suppressed. A 1 mm thick tungsten plate with a 50 $\mu$m slit opening is used as a slit mask to produce a beamlet, which is imaged 1.01 m downstream on a Ce:YAG screen. Beamlets from three slit positions are taken into account in the emittance calculations. More details of the measurement technique and calculations are in [16, 17].

Optimization of the longitudinal and transverse profile of the photocathode laser pulse plays an important role when attempting to reach small emittances. A pulse shaper producing laser pulses with longitudinal flat-top profile is used at PITZ. The typical laser pulse length is around 20 ps with a rise and decay time of about 7 ps. When a flat-top laser pulse is used, the measured emittance is reduced at least by a factor of two compared to emittances measured with a gaussian laser pulse [14]. In order to find an optimum balance between the thermal (initial) and the space charge induced emittance, the transverse size of the laser pulse has been varied. The optimal transverse laser profile is radially homogeneous with a size of $\sim$0.55 mm (rms).

Besides the laser profile, also the RF phase of the gun cavity with respect to the laser phase, as well as settings of the two solenoids need to be optimized. A systematic optimization of these parameters has been performed at PITZ for the RF gun now in use at the VUV-FEL. The minimum normalized average emittance ($\sqrt{\epsilon_x \epsilon_y}$) measured for a 1 nC bunch was around 1.7 mm mrad [6].

After the delivery of the VUV-FEL gun to DESY Hamburg, an other RF gun cavity, with a similar design, has been installed to PITZ. This cavity is operated with a higher gradient on the photocathode: 45 MV/m instead of 42 MV/m. This, in combination with some other subsystem upgrades, has resulted in an improved transverse emittance. Figure 2 shows measured horizontal ($\epsilon_x$) and vertical ($\epsilon_y$) normalized emittances as a function of the main solenoid current. A geometrical average ($\epsilon_{\rm tr} = \sqrt{\epsilon_x \epsilon_y}$) and results from ASTRA simulations [18] using a rotational symmetrical model are presented as well. The bucking solenoid is tuned to compensate the main solenoid field at the cathode for each main solenoid current. The RF phase is chosen to be close the phase providing the maximum electron beam energy. We can see that the behavior as function of the solenoid current agree with the prediction from simulations, and that the minimum measured average emittance is around 1.6 mm mrad.

### *Longitudinal phase space*

Besides the optimization of the transverse emittance, it is important to study and optimize the beam parameters also in the longitudinal phase space. At PITZ correlated measurements of the beam momentum and the temporal structure of the electron bunch (longitudinal bunch shape) are possible. The momentum distribution is measured on a Ce:YAG screen in a dispersive section of the spectrometer dipole (see Fig. 1). The temporal structure of the electron bunch is measured using a streak camera detecting light emitted when an electron beam traverses a Cherenkov radiator (silica aerogel). These measurements are possible both in the straight and in the dispersive section (see Fig. 1). Streak camera measurements in the dispersive section provide a combined measurement of the temporal and the momentum distribution of the electron bunch.

Figure 3 shows first results of longitudinal phase space

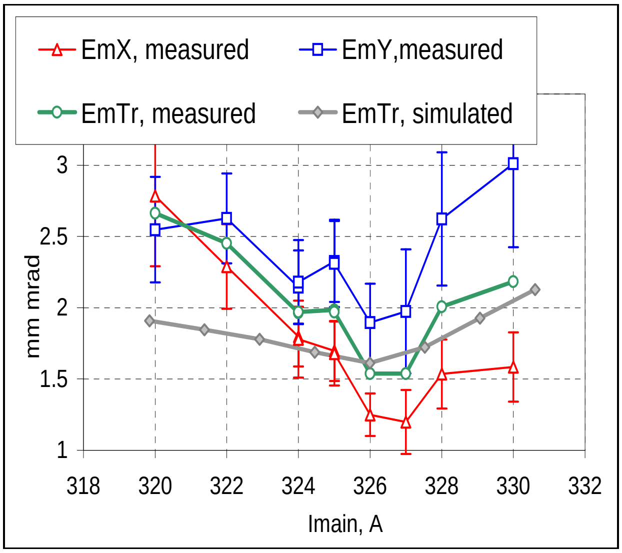


Figure 2: Normalized emittance measured at PITZ as a function of the main solenoid current. The electron beam momentum is 5.2 MeV/c, and the bunch charge 1 nC. The bucking solenoid current is optimized for each main solenoid current. Horizontal (red) and vertical (blue) normalized emittances as well the geometrical average $\sqrt{\epsilon_x \epsilon_y}$ (green) are shown. The grey curve is a result from simulations.

measurements. The left plot is the phase space distribution measured by the streak camera in the dispersive section. The right plot shows the simulated [19] phase space. We can see that the experimental results agree relatively well with the simulations. However, further studies and analysis are required in order to understand in detail the beam parameters in the longitudinal phase space. More details and recent results are in [15, 20].

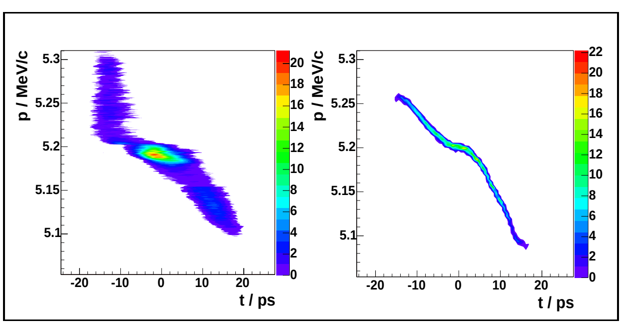


Figure 3: Measured (left) and simulated (right) longitudinal phase space. The vertical axis represents the electron beam momentum and the horizontal the temporal distribution of the bunch. Bunch charge is 1 nC.

### *Upgrade of PITZ (PITZ 2)*

Presently, the PITZ facility is being upgraded. The main goal of the upgraded facility (PITZ 2) is to further improve of the transverse emittance and to study in detail the emittance conservation scheme.

The 5 MW klystron providing RF power for the gun cavity is now replaced by a 10 MW klystron. With this new klystron it is possible to operate the RF gun with a higher accelerating field, which improves the beam quality due to reduced space charge forces. A second major upgrade is the installation of a booster cavity. With the booster presently installed at PITZ the beam energy can be increased up to ∼16 MeV. Later, with a special booster designed for PITZ, the beam energy can be further increased up to ∼30 MeV. The location of the booster is chosen such that the distance from the photocathode to the entrance of the cavity is identical to the corresponding distance at the VUV-FEL injector. The beam diagnostic sections are being upgraded as well. With the new diagnostics tools it will be possible to measure the transverse emittance by different methods in several locations along the linac. Also slice emittance measurements will be possible in the future. An upgrade of the photocathode laser system, including replacement of the flashlamps by diode-pumped amplifiers and improvements on the laser beam line, has been already done. A laser system providing longitudinal flat-top laser pulses with a very short rise and decay time (<2 ps) is under development. More details and the first results of the upgraded PITZ facility are in [21].

## THE VUV-FEL

In the present stage, the VUV-FEL linac consists of a laser driven photoinjector, five accelerator modules with eight 9-cell superconducting TESLA cavities, two magnetic chicane bunch compressors, and six undulator segments to produce SASE FEL radiation. Figure 4 shows a schematic overview of the linac. With this layout electron beam energies up to ∼730 MeV can be achieved. Later, one or two accelerator modules can be added to increase the beam energy up to 1 GeV. During the commissioning emphasis has been on lasing at a wavelength of 32 nm, which requires an electron beam energy of 445 MeV.

The RF gun is operated with a gradient of 41 MV/m. The longitudinal laser pulse shape is nearly gaussian with an rms size of ∼ 4.5 ps. Later, if required, a similar laser pulse shaper as tested at PITZ providing longitudinally flat-top laser pulses can be installed to the VUV-FEL laser system. A complete TESLA module with eight superconducting cavities, placed about 2.5 m downstream of the photocathode, is used as a booster. In order to make use of the matching conditions discussed above the first four cavities are operated with a moderate gradient (12 MV/m). The last four cavities accelerate with the nominal gradient of ∼20 MV/m increasing the electron beam energy to 125 - 130 MeV before the first bunch compressor. At the second compression stage, the beam energy is about 370 MeV. The design normalized emittance is 2 mm mrad.

More details of the VUV-FEL photoinjector are in [22].

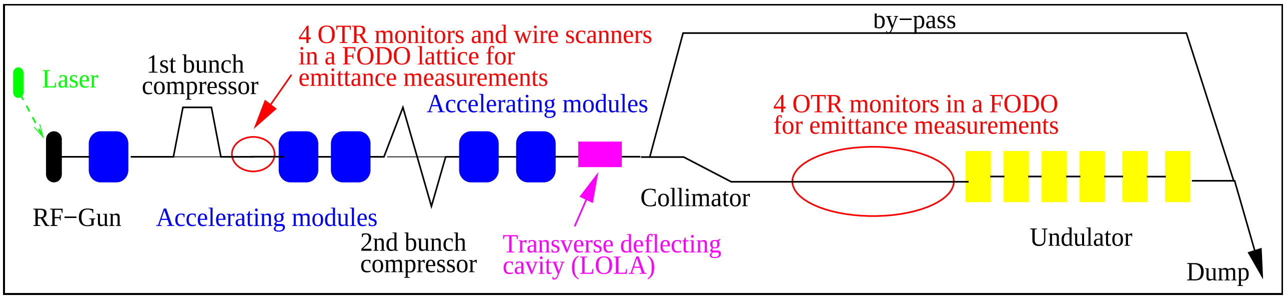


Figure 4: Present layout of the VUV-FEL linac (not to scale). Beam direction is from left to right. The total length is about 250 m. The LOLA cavity as well as the locations of the diagnostic sections dedicated to emittance measurements are indicated.

## *Emittance measurements*

Measurements of the transverse projected emittance are performed using a four-monitor method. In this method the transverse beam distribution (shape and size) is measured at four locations with a fixed beam optics. Along the linac there are two diagnostics sections dedicated to these measurements (see Fig. 4). The first one is a FODO lattice of six quadrupoles with a periodic beta function located downstream of the first bunch compressor at the beam energy of 127 MeV. The beam distribution is measured with four optical transition radiation (OTR) monitors combined with wire scanners. The second FODO lattice with four OTR monitors is upstream of the undulator at the full beam energy. The OTR monitor system is designed and constructed by INFN-LNF and INFN-Roma2 in collaboration with DESY. Detailed description of this system is in [23, 24, 25].

The transverse emittance is determined from the measured beam distribution and the known transport matrices using two techniques. The first one is based on least square fitting of the Twiss parameters and the emittance to the measured beam sizes. The second one uses tomographic reconstruction of the transverse phase space. The results obtained by both methods agree well with each other [26].

Since a small fraction of particles in the tails of the transverse beam distribution can have a significant influence on the transverse emittance, we are interested in, besides the emittance of the entire beam, the emittance of the high density core. This core is determined by cutting away 10% (an arbitrary choice) of particles in the tails of the two-dimensional transverse beam distribution. Horizontal and vertical emittances are calculated for the entire beam and for the core containing 90% of the beam intensity. All the calculations use the rms definition of the beam size.

Figure 5 shows the measured normalized horizontal ($\epsilon_x$) and vertical ($\epsilon_y$) rms emittances as well as the geometrical average ($\epsilon_{\rm tr} = \sqrt{\epsilon_x \epsilon_y}$) as a function of the current in the main solenoid. The measurements are performed in the diagnostic section after the first bunch compressor using OTR monitors. During these measurements the injector was operated with the nominal parameters, but it was not tuned to obtain the minimum emittance. The electron beam was transported through the bunch compressor without compression (on-crest acceleration in the first accelerator module). The beam energy was 125 MeV, and the bunch charge 1 nC. The experimental results are shown both for 100% and 90% beam intensity. The solid line is the result

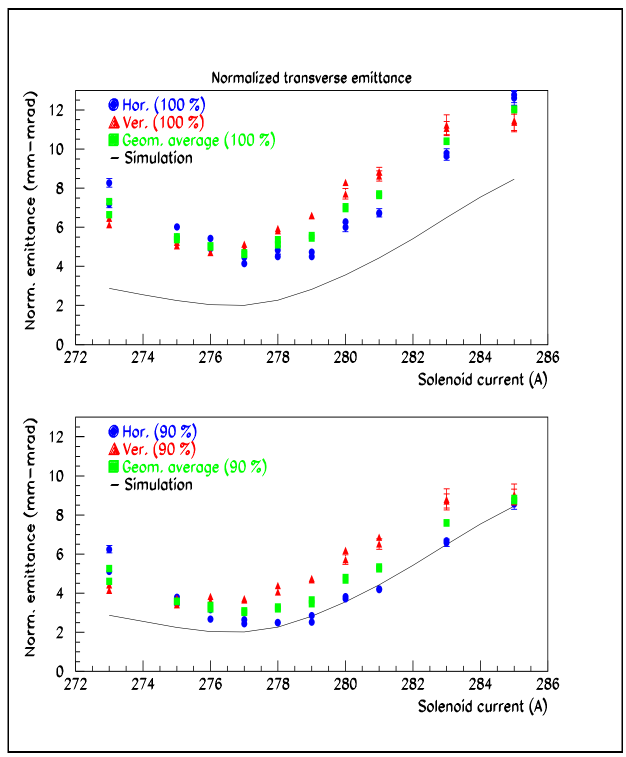


Figure 5: Normalized emittance measured at the VUV-FEL as function of the main solenoid current. Measurements have been repeated twice for each solenoid current. Electron beam energy is 125 MeV and bunch charge 1 nC. Bucking solenoid current is 20 A. Horizontal (blue) and vertical (red) normalized emittances as well the geometrical average $\sqrt{\epsilon_x \epsilon_y}$ (green) are shown both for the entire beam (top) and for the 90% beam intensity (bottom). The solid curve is a prediction from simulations. Emittances are calculated by the least square fitting technique, and the errors shown are statistical errors only.

from simulations [27] using 2 mm mrad normalized emittance. The observed behavior as a function of the solenoid current agrees well with the prediction from the simulation: the optimal solenoid current from the emittance point of view is 277 A, which corresponds to a magnetic field of 0.163 T.

In order to reach small emittances, we need to optimize, besides the laser and solenoid settings, also the beam injection to the first accelerator module. When the injector is carefully tuned, we regularly measure normalized emittances around 1.4 mm mrad for 90% of a 1 nC bunch at beam energy of 127 MeV. For the entire beam this value is typically around 2 mm mrad.

More details of the emittance measurements, as well as of the transverse electron beam diagnostics in general, are in [26], and a complete description of the emittance measurement set-up, image analysis, emittance calculations, and error analysis in [28].

When comparing the results obtained at PITZ and at the VUV-FEL, we need to keep in mind the differences in the measurement conditions. First of all, at PITZ flat laser pulses are used, while at the VUV-FEL the longitudinal laser pulse is shorter and nearly gaussian. Secondly, at PITZ the emittance has been measured and optimized at a low beam energy ($\sim$5 MeV) about 1.6 m downstream of the photocathode. At the VUV-FEL the emittance measurements are performed after the first accelerator module at the electron beam energy of 127 MeV about 29 m downstream of the cathode. The gradient and the location of the module is chosen such that the conditions fit for the matching conditions discussed above. The fact that the minimum emittance at PITZ and at the VUV-FEL is achieved with different setting of the solenoids can be explained by the emittance optimization at different locations. The emittances measured at PITZ and at the VUV-FEL agree with the expectations from simulations, and, taking into account the differences in measurement conditions, are consistent with each other.

Sofar, the emittance measurements at the VUV-FEL have been performed using the OTR monitors only. The commissioning of the wire scanners combined with the OTR monitors in the first FODO lattice is on-going, and a first cross-check of the results obtained by the OTR monitors and the wire scanners has been recently done showing a good agreement [26]. Optimization of the emittance measurement conditions in the second FODO lattice before the undulator has not yet finished, and therefore accurate emittance measurement have not yet been done there. Along the undulator there are seven wire scanners. The first tests to use these wire scanners for emittance measurements have been successfully done, and they are now available for emittance measurements.

### *Measurements of longitudinal bunch structure*

Measurements of the longitudinal bunch distribution are performed using different methods. In the injector, synchrotron radiation emitted by the last dipole of the first bunch compressor is guided out of the accelerator tunnel and used for bunch length measurements by a streak camera and an interferometer [29]. A detailed description of the interferometer measurements is in [30]. After the both bunch compressors, a slit providing coherent diffraction radiation can be inserted into the beam pipe. The coherent (THz) radiation is used for on-line measurements of the bunch compression by means of a pyrodetector, and it can be used for bunch length measurements with interferometers as well. Additional experimental set-ups using THz radiation are under construction.

In order to resolve the bunch structure at the full bunch compression, two sophisticated diagnostics tools have been implemented to the VUV-FEL linac. The first one, still under commissioning, uses electro-optical sampling technique [31], and the second one, described more in detail below, is based on the use of a transverse deflecting cavity [32].

A transverse deflecting cavity, a powerful tool to measure the bunch structure of a compressed electron beam, has been installed to the VUV-FEL in a collaboration between SLAC and DESY. It is a 3.66 m long disk-loaded S-band waveguide structure. This structure, called LOLA according to its designers, was built at SLAC in 1968. At the VUV-FEL, it is mounted between the last accelerator module and the collimator section (see Fig. 4). This structure provides a time dependent electric field, which deflects the electron beam transversally such that the temporal distribution of the electron bunch is transformed to a spatial distribution. The streaked beam image, having the temporal distribution in the vertical direction, is measured on an off-axis OTR screen downstream of the LOLA cavity. A kicker magnet is used to select only one bunch from the bunch train to be streaked. Depending on the transverse

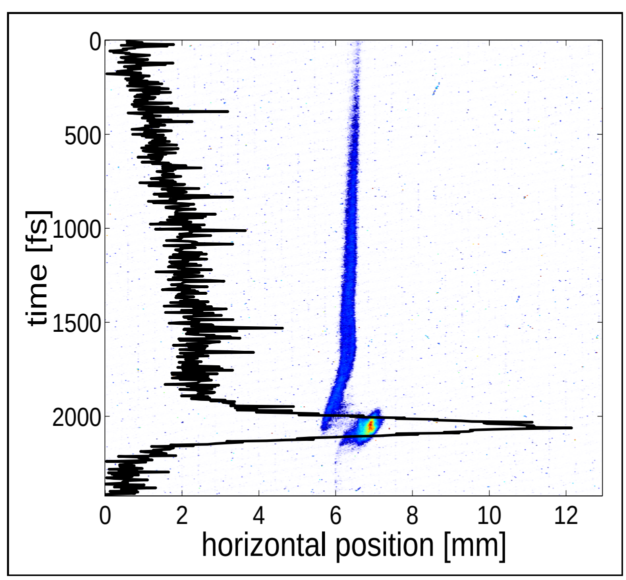


Figure 6: Longitudinal bunch distribution measured with the LOLA cavity during FEL operation.

focusing of the electron beam before the LOLA cavity, a resolution between 10 - 50 fs can be achieved.

Figure 6 shows an example of a streaked beam image measured during the FEL operation. The vertical direction represents the temporal structure of the bunch, which, as expected, has a leading spike and a long tail. The width of the spike depends on the FEL operation mode. In this example the width is ∼120 fs (FWHM). More details and results are in [33].

## SUMMARY AND OUTLOOK

In order to meet the high beam quality demands of the FELs, accurate characterization of the driving electron beam is essential. Dedicated beam diagnostics systems to measure and to optimize the beam parameters are implemented both at PITZ and at the VUV-FEL. In the transverse phase space the emphasis is presently on the measurements of the projected emittances, but both PITZ and the VUV-FEL have plans for slice emittance measurements in the future.

Since the VUV-FEL is already operated as a user facility, the time allocated to a detailed electron beam characterization is limited. Therefore, the emphasis of beam diagnostics will be more and more on the on-line measuring and monitoring of the beam parameters. The upgraded PITZ facility will continue detailed studies of the beam parameters and further develop high brightness electron sources.

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