FIRST LASING AT 32 NM 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. It is based on the TTF-FEL, which was in operation until end of 2002 providing a photon beam for two pilot experiments in the wavelength range of 80 to 120 nm.

In its final configuration, the new VUV-FEL is designed to produce SASE FEL radiation with a wavelength down to 6 nm with high brilliance. The commissioning started in fall 2004, and in January 2005 succeeded in first lasing in the SASE mode at a wavelength of 32 nm with a radiation power close to saturation. This is a major milestone of the facility and of SASE FELs in general.

This contribution reports on the present electron linac driving the FEL, on properties of the electron beam and on the characterization of the FEL photon beam.

INTRODUCTION

The VUV-FEL project at the TESLA Test Facility (TTF) at DESY [1] is the first user facility for VUV and soft X-ray coherent light experiments providing an impressive peak and average brilliance. The SASE process generates ultra-short coherent radiation pulses in the femtosecond range with peak powers in the GW level opening new fields of experiments in a broad range of scientific disciplines.

The VUV-FEL is also a pilot facility for the European XFEL project [2] and a test bed for further research and development for linear collider related superconducting accelerator technologies.

It is based on the TTF-FEL [3, 4], which provided beam until end 2002 for user experiments in the wavelength range of 80 to 120 nm [5, 6]. In 2001, saturation has been achieved at a wavelength of 98.1 nm [7]. The experiments carried out lead to out-standing results in atomic cluster [8] and ablation experiments [9].

The TTF-FEL has been completely redesigned to meet the demands on beam energy and beam properties for lasing down to 6 nm. For the present start-up phase, emphasis is given on lasing around 30 nm with smaller wavelengths down to 12 nm being within the present energy reach. The start-up installation has been completed in 2004, and will be finalized in 2006 with an additional accelerating module to reach an electron beam energy of 1 GeV required for 6 nm operation.

After the commissioning runs in 2004 and early 2005, first lasing has been achieved at a wavelength of 32 nm in January 2005 [10]. Since then, the VUV-FEL has been optimized to serve the first user experiments which started in June 2005.

Figure 1 gives a schematic overview of the present configuration of the linac. Table 1 summarizes the present beam and FEL properties for the start-up lasing around 30 nm and the design goal for 6 nm. For a more detailed discussion of parameter choices refer to [1, 11].

In the following, main sections of the linac are described, starting from the injector down to the undulator and photon diagnostic section.

THE LINAC

Injector

Based on the experience with the TTF phase 1 injector [12], the injector has been redesigned to meet the tighter demands on the electron beam quality for the VUV-FEL [13]. The design follows the proposal for the XFEL [14]. The performance of the injector is crucial for the successful generation of FEL radiation. For this reason, a photoinjector test facility (PITZ) [15] has been set-up to optimize electron sources for FELs and other applications. The injector has been successfully commissioned in the first half of 2004.[16]

Some electron beam properties required are listed in Table 1. Most important is to generate a train of electron bunches with a charge of 1 nC each and a normalized transverse emittance of less than 2 μm. The bunch train length

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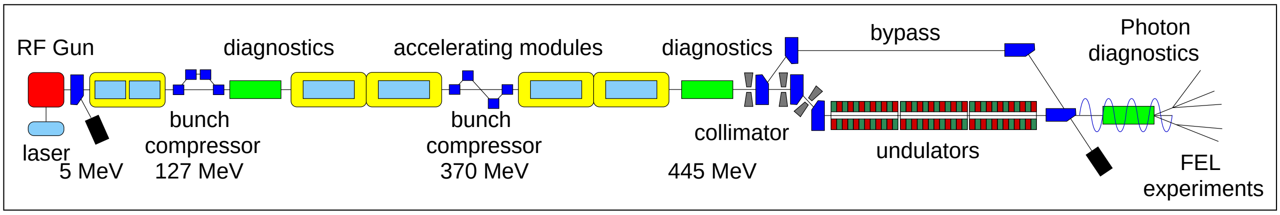

Figure 1: Schematic overview of the VUV-FEL linac (not to scale). Beam direction is from left to right, the total length is about 250 m.

Table 1: Present parameters of the VUV-FEL (start-up). For comparison, the design parameters for the femtosecond mode of operation for 30 nm are shown as well (from [11]). (The peak brilliance, peak power, and peak photon flux are calculated from the average achieved photon pulse energy, where the data are most complete.)

		start-up	design
Electron beam			
Energy	MeV	445	450
Peak current	kA	2.0	1.3-2.2
Emittance, norm. (x,y)	μm rad	2-4	1.5-3.5
Nb. of bunches/train		30	7200
bunch train length	ms	0.03	0.8
Rep. rate	Hz	2	10
ΔE/E (rms)	%	0.1	0.1
Undulator			
Period	cm	2.73	
Gap	mm	12	
Peak magnetic Field	T	0.48	
K		1.23	
total length	m	27.3	
FEL radiation			
Wavelength	nm	32	30
Max. pulse energy	μJ	40	50-150
Average pulse energy	μJ	16	
spot size (fwhm)	μm	$\approx$ 150	180-270
divergence (fwhm)	μrad	160	140-160
Bandwidth (fwhm)	%	0.8	0.8
Pulse duration (fwhm)	fs	25	15-50
Peak Power	GW	0.6	2-4
Peak photon flux	ph/s	$1{\cdot}10^{26}$	$3\text{-}6{\cdot}10^{26}$
Peak spectral Brilliance	$\star$	$\approx 10^{28}$	$\approx 10^{29}$

* photons/s/mrad^2/mm^2/(0.1 % bw)

of 800 μm and the repetition rate of up to 10 Hz are adapted to the superconducting TESLA accelerating structures.

A normal conducting laser-driven photocathode RF gun provides a rapid acceleration from the cathode and allows to generate a low emittance beam from the source.

The RF gun and an upgraded laser system have been successfully tested and optimized at PITZ [15] and installed at the VUV-FEL in January 2004. It is a 1.5 cell L-band cavity (1.3 GHz, TM_{010} mode) powered by a 5 MW klystron. A longitudinal coupler is used to keep the cylindrical symmetry around the beam axis as perfect as possible. The RF gun is operated with an RF power of 3 MW (41 MV/m on the cathode) and an RF pulse length of up to 0.9 ms. A low level RF system based on digital signal processors reads the forward and reflected power from the gun and regulates the RF power and RF phase in the gun by acting on the low level RF input to the klystron with a vector modulator. The phase stability achieved is below 0.5°, the amplitude stability within 0.1 %.

A Cs_2Te photocathode is inserted into the RF gun backplane via a load-lock system and can be changed if required. The cathode quantum efficiency achieved (for UV light) is initially high (more than 5 %) and drops to a level of 1 % after months of usage.

The laser is based on a pulsed mode-locked pulse train oscillator synchronized to the 1.3 GHz RF of the accelerator. The phase stability is better than 0.5 ps. A chain of linear Nd:YLF amplifiers provides the laser pulse energy to convert the initial infrared wavelength into UV (262 nm) with a single pulse energy of about 1 μJ required for a charge of a few nC on Cs_2Te. The system produces pulse trains with up to 800 μs length at a repetition rate of up to 10 Hz. The pulse spacing is usually 1 μs (1 MHz), a 9 MHz mode is in preparation. The charge fluctuation of a single electron bunch from shot to shot is better than 2 % rms, if averaged over a train better than 1 %. The pulses length in the UV measured with a streak camera is $\sigma_l = 4.4 \pm 0.1$ ps.

A complete TESLA module with eight accelerating structures boosts the beam energy to 127 MeV before the first bunch compressor. With the digital feedback system regulating the phase and amplitude of the accelerating structures, the energy stability $\delta E/E$ is better than $8.5{\cdot}10^{-4}$ rms. The uncorrelated energy spread has been estimated to be smaller than 25 keV, probably limited by the resolution of the present imaging system.

The uncompressed rms bunch length has been measured with a streak camera to be 1.7±0.2 mm as expected.

A small transverse emittance below 2 μm normalized is achieved by two measures. A solenoid (0.163 T) compensates the emittance growth induced by space charge in the drift after the gun. The beam is then matched into the acceleration section [17] which is operated with a moderate gradient of 12 MV/m in the first four cavities.

Bunch compressors

The peak current of the uncompressed bunch is about 70 A. In order to achieve a peak current exceeding 1 kA, a compression of the bunch using magnetic chicanes is done in two steps at energies of 127 MeV and 370 MeV. Care is taken to avoid an unacceptable emittance growth due to space charge, wakefield, and coherent synchrotron radiation effects.[18, 11]

The rms bunch length in the first accelerating section before compression is long compared to the RF wavelength (about 2 mm or 3° in RF). The beam is accelerated about 10° off-crest in order to impose an energy chirp along the bunch for compression. Due to the length of the bunch and the sinusoidal RF field, a curvature in the energy-phase plane develops. To remove this curvature, it is planned to install a superconducting third harmonic cavity (3.9 GHz) [19] before the first bunch compressor. This cavity is not available for the initial run this year.

However, the compression with the imposed curvature leads to a bunch with a sharp high current spike and a long tail. Moreover, varying the compression ratio in the two bunch compressors, a tailoring of the spike shape is to some extend possible. This effect has already been experimentally verified at TTF phase 1 [20] and successfully used for SASE operation [6, 21].

Therefore, we follow – until the third harmonic cavity is installed – the TTF phase 1 femtosecond mode of operation [11].

Undulator

Single pass high gain FELs require long undulator systems. The VUV-FEL undulator system consists of six modules with a length of 4.5 m each [22]. The fixed gap is 12 mm with a peak magnetic field of 0.48 T (K=1.23) realized with permanent NdFeB magnets. The undulator period is 27.3 mm. In contrast to TTF phase 1, the undulators have no internal focusing. A pair of electromagnetic quadrupoles between each of the six modules provides a large acceptance in beam energy. In terms of FEL radiation it covers the wavelength range of 120 to 6 nm. Each quadrupole doublet is aligned on a stable granite base plate together with beam position monitors and a vertical and horizontal wirescanner. The absolute alignment in respect to the undulator axis is better than 100 μm. The SASE process requires an alignment of the electron beam with the undulator axis of better than 20 μm. Therefore, the quadrupoles are equipped with movers allowing a fine adjustment of their position.

A collimation section [23] protects the undulators from radiation due to off-energy and off-orbit particles. The design includes two copper collimators in the straight and two in a dogleg section allowing to collimate off energy particles as well. The energy acceptance is $\pm$3 %.

Diagnostics

The linac includes a large variety of diagnostic tools to measure the transverse and longitudinal beam properties, beam positions, current etc.

Remarkable results have been achieved in the measurements of the transverse projected emittance and the longitudinal bunch structure.

The transverse beam size is measured using optical transition radiators (OTR). Twenty-four stations with movable radiators are installed, equipped with a high resolution imaging system each [24].

An impressively small transverse emittance for the uncompressed beam is measured in the injector at 127 MeV. The normalized projected rms emittance for a 1 nC bunch is ϵ_n=1.4 μm [25]. For this analysis, 90 % of the bunch intensity is used, the statistical error is 4 %, the systematic error estimated with 6 % [26].

A powerful method to measure the bunch length is a deflecting cavity integrated into the linac. At 445 MeV just before the collimation section, an S-band deflecting cavity [27] (length 3.66 m) in combination with an OTR beam size monitor is installed. The resolution of the system is smaller than 15 μm. First measurements of the longitudinal bunch structure reveals a sharp spike with a length of 36 μm or 120 fs (fwhm) and a long tail of 2 ps. The longitudinal structure varies from run to run depending on the specific tuning of the machine. Please refer to [28] for details.

Photon diagnostics

Another important diagnostic section is located in the FEL beam line to measure the properties of the FEL radiation. An overview of the various tools is given in [29].

An important instrument for tuning the onset of laser amplification and optimizing the lasing is a detector based on gold wires and a micro-channel plate (MCP) [30]. The dynamic range of this detector is sufficient to cover several orders of magnitude of radiation energy, from spontaneous (7 nJ for 1 nC) to the amplified emission (50 to 100 μJ). The detector has been carefully calibrated, its relative accuracy is in the order of 1 %. The radiation energy has been cross-calibrated with the gas monitor detector which has an absolute measurement uncertainty of 25 %. After calibration, the energies measured with both methods agree within 5 %.

View screens using Ce:YAG crystals are placed at various locations. A monochromator is used to measure single shot spectra. It is equipped with an intensified CCD camera and has a resolution of 0.02 nm with an absolute calibration error of less than 0.03 nm [31].

Experimental Hall

The FEL experimental hall is presently equipped with three experimental stations. Two more will follow in the near future. A variety of experiments in basic and applied research of multiple scientific fields, from life science, chemistry to physics are scheduled including pump-probe experiments. Three experiments already started to take data; their results will be published elsewhere.

OPERATION AT A WAVELENGTH OF 32 NM

In January 2005, lasing at 32 nm has been observed for the first time. Figure 2 shows the image of a single VUV-FEL pulse on a Ce:YAG crystal. The pattern of the gold mesh in front of the crystal is clearly visible. From the distance between the grid wires a size of 3 mm (fwhm) is measured yielding an angular divergence of 160 μrad (fwhm). The spot size at the undulator exit is estimated to be about 150 μm (fwhm).

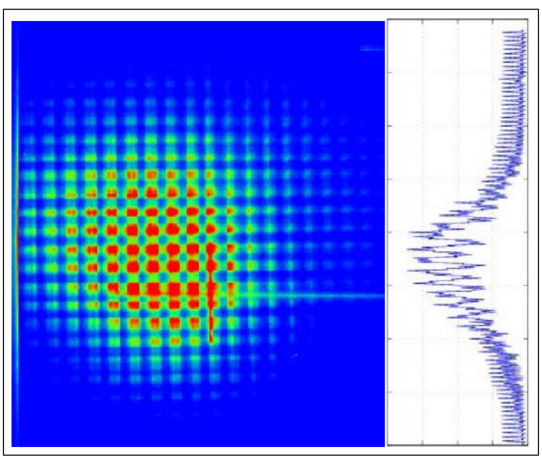

Figure 2: Image of a the FEL beam on a Ce:YAG crystal (single shot) and its projection.[10] The gold mesh of the radiation detector in front of the screen is visible and allows to estimate the width of the beam to 3 mm (fwhm) at 18.5 m distance from the undulator (wire distance 0.31 mm). This results in an angular divergence of 160 μrad (fwhm).

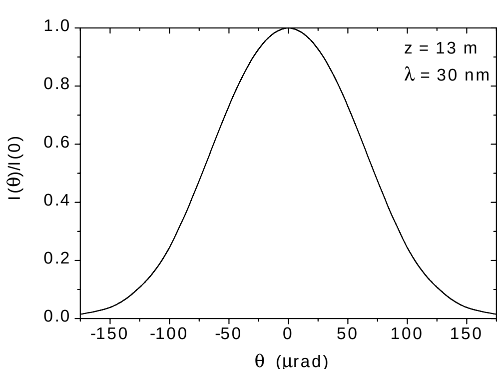

Figure 3: Simulated intensity distribution of the FEL radiation in the far zone.[11] The angular divergence is 150 μrad (fwhm) in good agreement with the measurement.

The measured angular divergence fits well to the estimate from simulation (Fig. 3). We conclude, that the beam is close to the diffraction limit and thus has a high degree of transverse coherence. First measurements of the coherence with a slit system confirm this.

Energy in the radiation pulse

The energy of the SASE FEL radiation pulses fluctuates due to the statistical nature of the SASE process starting from noise. When the fluctuations caused by machine induced instabilities of the beam are small, we can measure this fluctuation. Figure 4 shows the measured energy of the FEL radiation during a certain time period together with a histogram of the same data yielding a probability distribution $p(E)$ of the energy E. From theoretical considerations of the SASE process [32], the probability follows the distribution $p(E) = M^M/\Gamma(M)\ E^{M-1}e^{-ME}$ with the gamma function $\Gamma(M)$, E is the energy normalized to its average. The parameter $M = 1/\sigma_E^2$ is interpreted as the number of modes in a radiation pulse. In the case shown, the measured rms width σ_E of the distribution is 49.6 % (normalized to the average energy) yielding the estimate of the number of lasing modes M = 4.1. The measured distribution follows the expectation of a high-gain FEL operating in the exponential regime.

In the example shown in Fig. 4, the average energy was 1 μJ. This is well within the exponential regime of the FEL, where the Gamma-distribution defined above should apply. After tuning the VUV-FEL, an average energy of 16 μJ with a peak energy of 40 μJ has been reached in June 2005. At the same time, the width of the energy distribution is getting smaller, indicating the approach of saturation.

Radiation Spectra

From the statistical analysis of the energy fluctuation, we cannot distinguish between transverse and longitudinal modes. Given the high degree of transverse coherence supported by the measurement of the angular divergence, we estimate, that about 2 or more modes should show up as spikes in the frequency domain. Figure 5 shows examples of measured single shot spectra supporting this assumption. The data agree well with simulations of the FEL process in the exponential regime (Fig. 6).

The duration of one longitudinal spike $\tau_{\rm rad}$ itself is too short to be measured directly. However, it can be estimated from the width of the single shot spectra using the relation $\tau_{\rm rad} = 2\pi/\delta\omega$. The fwhm width of the spectra is typically 0.25 nm (or 0.8 % at 32 nm). This leads to a spike duration of $\tau_{\rm rad}$ = 14 fs. With the presence of several modes, the total length of the radiation pulse is roughly speaking increased by the number of modes. The results agree well with simulations of the process. Including the presence of more than one longitudinal modes, the total pulse length is estimated with 25 fs. Averaging several single shot spectra yield a center wavelength of 31.8 nm and a width of 0.275 nm.

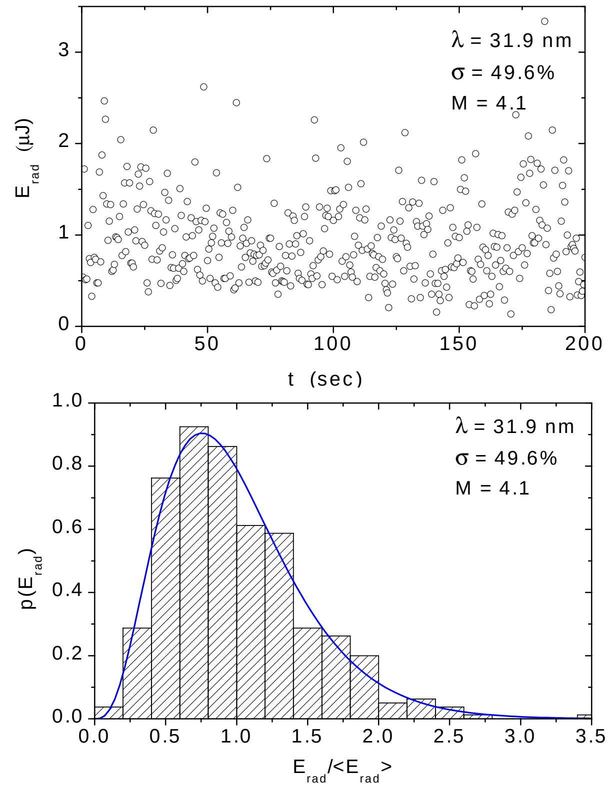

Figure 4: Example of the measured energy in the FEL radiation pulses for a certain period of time (top). The same data normalized to the average energy are shown as a histogram giving the probability distribution (bottom).[10] The rms energy fluctuation σ of 49.6 % gives the number of lasing modes M of 4.1, which determines the Gamma-distribution drawn as a solid line. (The data bins are scaled such that the area is equal to the integrated Gamma-distribution.)

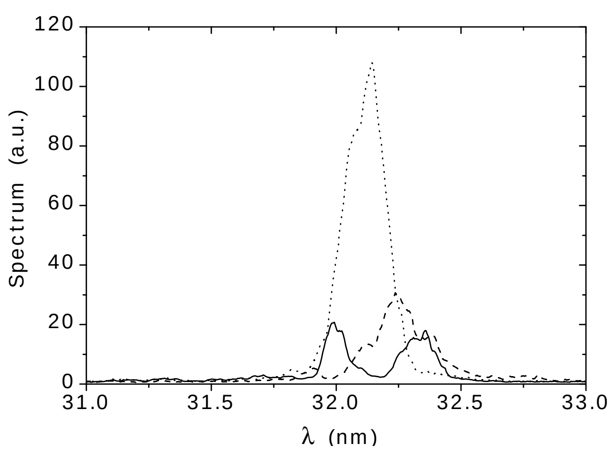

Figure 5: Example of three measured single shot spectra with different line shapes.[10] The center wavelength is 32 nm, the spectral width typically 0.25 nm.

With an average measured energy of 16 μJ, this correspond to 0.6 GW average power. The maximum energy

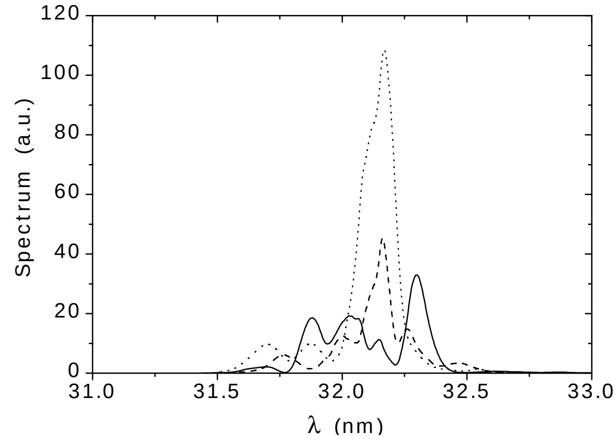

Figure 6: Simulation of the spectra operating in the exponential regime.[11] They are in good agreement with the measurements.

of 40 μJ measured so far would lead to a peak power of 1.6 GW. However, the analysis of the spectra for this case indicate a larger total length by a factor of 2 reducing the peak power to 0.8 GW. The numbers are summarized in Table 1.

A figure of merit for many experiments is the brilliance, the spectral photon flux per area and solid angle. With the data given in Table 1, the peak brilliance at the exit of the undulator amounts to $B = 2.7{\cdot}10^{28}$ photons/s/mrad^2/mm^2/(0.1 % bw) with a large uncertainty due to the rough estimate of the spot size at the undulator. This is several orders of magnitude above the state-of-the art synchrotron radiation sources.

Assuming fully coherent radiation, the product of the radiation beam area and the solid angle is given by $(\lambda/2)^2$. Using B_c = spectral photon flux/ $(\lambda/2)^2$ we get $B_c = 4.6{\cdot}10^{28}$ photons/s/mrad^2/mm^2/(0.1 % bw). This is only by a factor of 2 larger then the calculated brilliance from the measured angle and estimated spot size. This indicates a good coherence and the presence of more than one transverse modes, in agreement with the statistical analysis discussed above.

The SASE process also generates higher harmonics radiation. In June 2005, the second and third harmonics have been measured for the first time. Figure 7 shows their averaged spectra. The center wavelengths are 15.86 nm and 10.53 nm respectively, the spectral width is 1.1 % (fwhm) in both cases. The monochromator has been calibrated for wavelengths down to 20 nm, the calibration for smaller wavelengths has been extrapolated from this. Therefore, the absolute wavelength is preliminary.

SUMMARY AND OUTLOOK

The VUV-FEL at DESY started to produce laser-like radiation with a wavelength of 32 nm and a peak brilliance orders of magnitude above the state-of-the art synchrotron radiation sources. Moreover, the radiation pulses exhibit

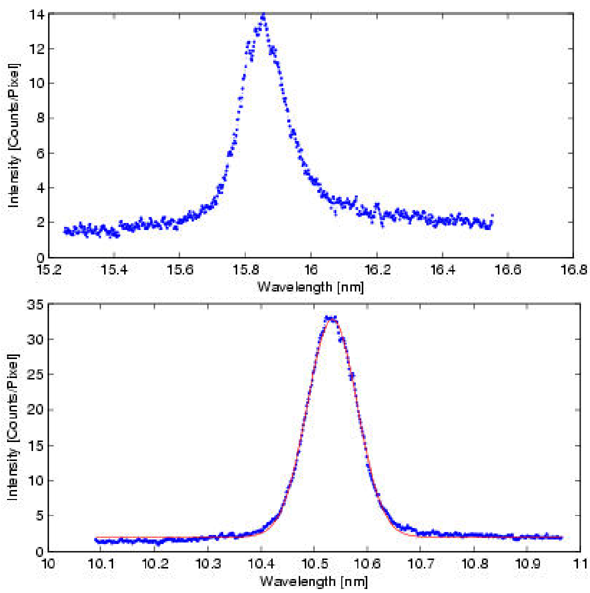

Figure 7: Measured average spectra of the second (top) and third (bottom) harmonic of 32 nm. The center wavelengths are 15.86 nm and 10.53 nm respectively.

spikes with a width in the 10 fs range opening a new window of research.

The facility includes five beamlines for experiments. Three beamlines have been commissioned so far, experiments started to take data. The other beamlines will be commissioned soon. For this year, several experiments are scheduled, including pump-probe experiments.

Later in 2006, an addition accelerating module will be installed which enables beam energies up to 1 GeV opening the window to wavelength down to 6 nm. The injector will be upgraded with a third harmonic superconducting cavity to improve the longitudinal structure of the beam. Additional equipment and undulators will be added for a seedings scheme to provide fully coherent radiation.

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