2 TTF/FLASH in the XFEL context

2.1 Historical background

In the early 90s, the Tera-Electronvolt Superconducting Linear Accelerator (TESLA) Test Facility (TTF) was established by the international TESLA collaboration as a test bed for studies of superconducting linac technology for a future linear collider. To this end, work at TTF **[2-1]** was focused on achieving an accelerating gradient around 25 MV/m and on the development of techniques to manufacture such accelerating components in a reliable and cost-effective way. Furthermore, experimental verification of the components' performance in terms of field quality, beam dynamics, reliability, diagnostics tools and control procedures was a key objective.

It was realised very soon, that a superconducting accelerator like TTF would be perfectly suited to drive a free-electron laser (FEL) at wavelengths far below the visible, mainly due to:

- the large iris diameter of the accelerator cavities – wake field effects, eventually degrading the electron beam quality, are very small compared to standard normal conducting cavities;
- its excellent power efficiency – a superconducting linac can be operated at very high duty cycle, up to continous wave operation, a fact that allows for very high average brilliance and for large flexibility in terms of timing structure.

Based on these superior properties, the vision from the very beginning was to develop superconducting FEL technology in a way applicable within a large range of wavelengths, down to the x-ray regime **[2-2]**. As there are no normal incidence mirrors at very short wavelengths, the Self-Amplified Spontaneous Emission (SASE) principle **[2-3, 2-4]** was the most promising concept to adopt.

At that time, the SASE principle was experimentally demonstrated only at wavelengths in the microwave regime **[2-5]**. The direct jump to Ångstrom wavelengths, i.e. a jump by seven orders of magnitude in wavelengths, was considered too ambitious. Thus, a jump by four orders of magnitude was proposed **[2-6]** to reach 100 nm, a wavelength regime where the SASE FEL principle is competitive with other types of lasers. This could be done with the available TTF accelerator by adding a suitable electron source, a bunch compressor, and a 15 m long undulator. This installation was called TTF FEL, Phase 1.

However, besides proving the principle, it was even more important to make scientific use of this new type of radiation source as soon as possible. Thus, in a second phase, the scientifically attractive vacuum ultraviolet (VUV) wavelength range between 6 nm and 40 nm was to be achieved. To this end, the TTF linac had to be upgraded to 1 GeV maximum beam energy, an additional bunch compressor and a 30 m long undulator had to be installed, and a hall for user experiments had to be built. A proposal **[2-7]** of a two-stage realisation of a SASE FEL user facility based on the TTF, as outlined already, was endorsed by an international advisory committee. This facility was called VUV-FEL. In April 2006, it was renamed as Free-electron LASer in Hamburg (FLASH).

2.2 TTF FEL, Phase 1

2.2.1 Accelerator R&D

From the very beginning, the overall design of the TESLA superconducting accelerator (linac) was based on nine-cell cavities made from pure Niobium, tuned for the TM010 π-mode at 1.3 GHz. Eight of such 1.04 m-long elements were assembled into one cryostat module, together with a superconducting magnet package (consisting of quadrupoles, dipole correctors and a beam position monitor), radio frequency (RF) input couplers, and various sensors. While alternative configurations were investigated within the R&D programme at TTF, this general layout was so successful that it has remained unchanged up to now.

At the beginning, the TESLA cavities typically achieved accelerating gradients around 15 MV/m, with considerable fluctuations. The improvement up to the present-day values beyond 35 MV/m was mainly due to intensive research on the treatment of both the bulk and the surface of the Niobium material. Details are given in Section 4.2.1.3 of this report.

2.2.2 FEL research

The TTF FEL installation in Phase 1 consisted of a low-emittance, laser-driven RF-gun, a pre-accelerator followed by the first magnetic bunch compressor chicane, two TESLA accelerating modules separated by a second magnetic bunch compressor chicane, and a 15 m long undulator, as illustrated in Figure 2.2.1.

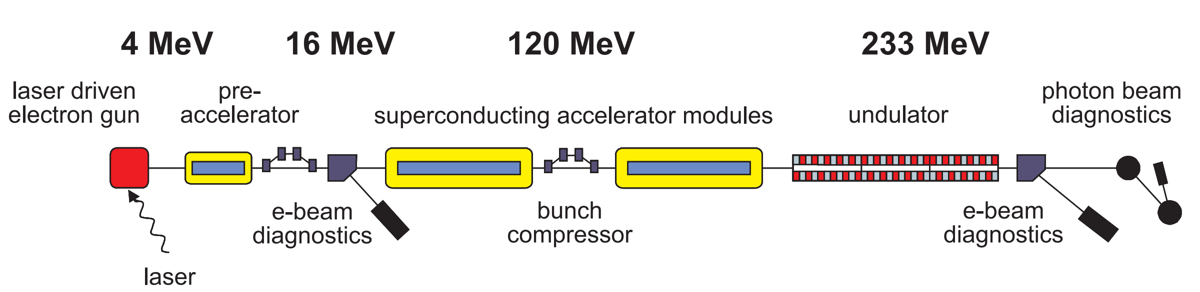

Figure 2.2.1 *Schematic layout of Phase 1 of the SASE FEL at the TTF at Deutsches Elektronen Synchrotron Laboratory (DESY), Hamburg. The total length was 100 m.*

The undulator was a permanent-magnet device **[2-8]** with a 12 mm fixed gap and an undulator parameter of K = 1.17. In order to achieve the minimum FEL gain length, the optimum beta function $\beta_{opt} \approx$ 1 m had to be realised inside the undulator. To this end, permanent-magnet quadrupole fields were superimposed on the periodic undulator field in order to focus the electron beam along the undulator. The undulator system was subdivided into three segments, each 4.5 m long and containing ten quadrupole sections with alternating gradients. The vacuum chamber made from extruded aluminium profiles incorporated ten beam position monitors and ten dipole magnets per segment for orbit steering.

In addition, two pick-up type beam position monitors, and horizontal and vertical wire scanners were installed at the entrance and exit of each undulator segment, with the wire positions aligned with respect to a stretched wire determining a straight reference line. Also, an electron beam collimator was installed in front of the undulator to protect it from radiation damage by electrons with large betatron amplitudes, generated, for instance, by dark current.

2.2.3 Results

The TTF FEL, Phase 1 demonstrated a unique femtosecond mode of operation which was not considered at an early design stage of the project **[2-7]**. Due to nonlinear compression and a small local energy spread, a short high-current (3 kA) leading peak (spike) in the bunch density distribution has been produced by the beam formation system **[2-9]**. Despite strong collective effects (of which the most critical was the longitudinal space charge after compression), this spike was bright enough to drive the FEL process up to saturation for wavelengths around 100 nm **[2-10 – 2-12]**. In addition to the possibility for production of high-power femtosecond pulses, this mode of FEL operation demonstrated high stability with respect to drifts of machine parameters.

The TTF FEL, Phase 1 delivering a peak brilliance of 2×10^{28} photons/(s mrad^2 mm^2 (0.1% bandwidth)) between 80 and 120 nm, was readily used to perform pioneering experiments **[2-13, 2-14]**.

A most important result was the perfect agreement between FEL theory and observation in the wavelength regime around 100 nm **[2-9 – 2-12]**. Figure 2.2.2 shows both the theoretical and experimentally determined gain curve for a wavelength of 98 nm.

By variation of bunch compressors settings it was possible to control the width of the lasing fraction of the electron bunch, resulting in a controlled variation of the radiation pulse length between 30 fs and 100 fs (FWHM). As a consequence, the radiation pulse consisted of only a few optical modes, as seen from single pulse spectra (Figure 2.2.3).

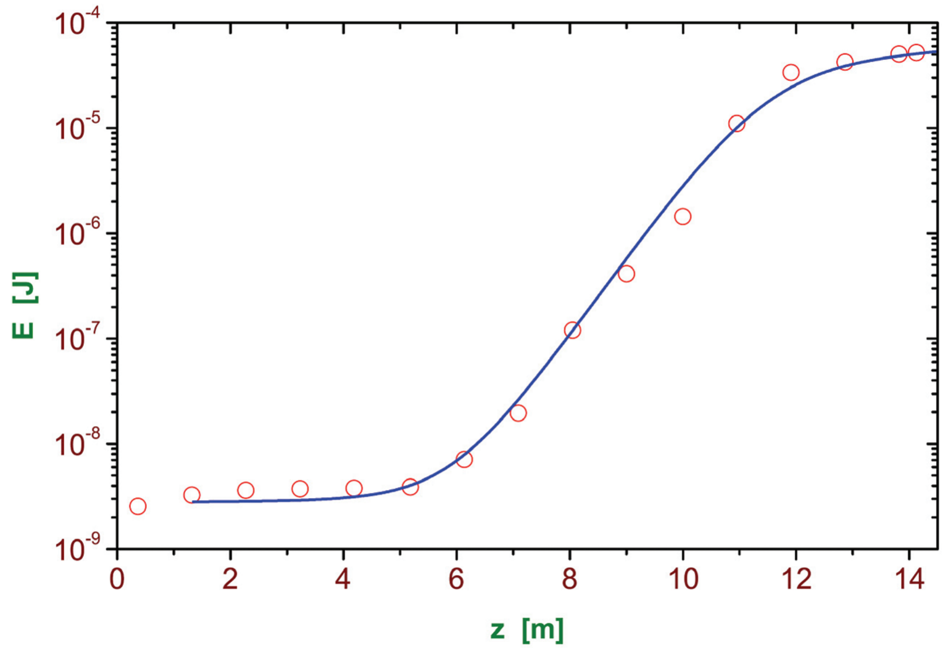

Figure 2.2.2 Average energy in the radiation pulse as a function of the active undulator length at the TTF FEL, Phase 1. Circles: experimental results. Solid curve: numerical simulation using measured electron beam parameters. The wavelength for this measurement was chosen at 98 nm.

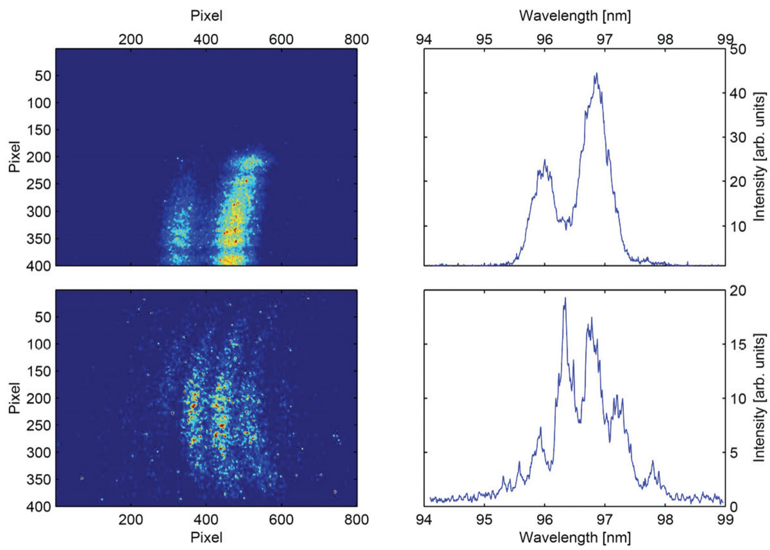

Figure 2.2.3 Spectra from short (top) and long (bottom) FEL pulses, taken at TTF FEL, Phase 1. On the left hand side, the CCD image of the dispersed FEL radiation in the exit plane of the monochromator is shown in a false color code. The dispersive direction is the horizontal one. On the right hand side, the spectra are evaluated quantitatively along the horizontal centre line of the CCD image. The numbers of modes are different: for short pulses (top), there are, on average, 2.6 modes, in the long pulse setting, there are six modes on average.

2.2.4 Experience from commissioning procedures

It took several months from the first observation of spontaneous radiation to the demonstration of lasing. The main reason for this difficulty was insufficient orbit control inside the undulator and incomplete knowledge about the detailed 6D (six-dimensional) phase-space distribution of the electron bunch.

While the combination of undulator field and quadrupole field was a very elegant solution, it left only one way for beam-based alignment of position monitors, namely by changing the beam energy drastically. This procedure turned out to be impractical at TTF FEL, Phase 1 in reality. As the number of free parameters to be varied for finding first lasing is very large, it was extremely important for machine operators to have information on the orbit they could really trust. Therefore, a large number of precisely aligned wire scanners, representing an entirely independent mechanical system for orbit control, turned out to be indispensable.

The most critical step has been to find the onset of laser amplification. For this purpose, a radiation detector equipped with a microchannel plate (MCP) has been used, which features a dynamical range of seven orders of magnitude and covers the entire range of intensities from spontaneous emission up to FEL saturation **[2-15]**. With only little gain present, the FEL beam is hidden in the powerful background of spontaneous undulator radiation. Thus, it was essential that the MCP device was sensitive enough to detect even a few percent of growth in radiation energy. In principle, it should have been possible to achieve a much better suppression of spontaneous background by the insertion of an iris collimating the opening angle seen by the detector. In view of the uncertainty in prediction of the pointing direction of the FEL photon beam, this way was not taken.

While TTF FEL, Phase 1 was running, the design of FLASH was finished in detail, and components were fabricated and tested.

2.3 TTF FEL, Phase 2 – FLASH

2.3.1 Design

While the original proposal was already published in 1995, the actual start of the installation work for conversion of TTF FEL, Phase 1 into FLASH was in 2002. Based on the experience gained, the design was modified from the original proposal, and a more accurate prediction of beam dynamics and FEL performance could be given. This was described in an update to the 1995 design report **[2-16]**. After commissioning the injector and the first bunch compressor, these predictions could be even more refined **[2-17]**. The key modifications were:

- a larger hall for five photon beamlines and experimental facilities was planned;
- a beamline section giving room for later installation of a seeding option, was inserted;

- during electron beam commissioning, and during beam time dedicated to accelerator research, the electron beam has to be transported down to the beam dump without making any use of the undulator. At TTF FEL, Phase 1, lots of time was wasted in finding a way of keeping the beam losses in the undulator at a tolerable level during such modes of machine operation. Thus, a 100 m long bypass beamline was added to optionally bypass the undulator and seeding section;
- At TTF FEL, Phase 1, off-momentum particles were a source of radiation damage to the undulator, that could not be removed in the straight collimator section. Thus, the collimator for FLASH includes a dispersive dog-leg section;
- the focusing in the undulator section was changed from a superimposed permanent-magnet lattice to electro-magnetic quadrupoles located in the space between the undulator segments. In this way, beam-based alignment can be done without changing beam energy. The minimum average beta function values that can be achieved with this focusing lattice is approximately 4 m. This comes sufficiently close to the optimum beta function of $\beta_{opt} \approx$ 3 m, calculated for FLASH parameters. Except for this modification, the undulator design remained unchanged.

Progress on the TESLA accelerator R&D has been reported in the "TESLA Reports" series (351 reports so far), while the "TESLA-FEL Reports" series is dedicated to FEL- specific work (109 reports by now). In addition, more than 1,000 papers have been published on TTF/FLASH issues since 1993. Figure 2.3.1 illustrates the overall layout of FLASH.

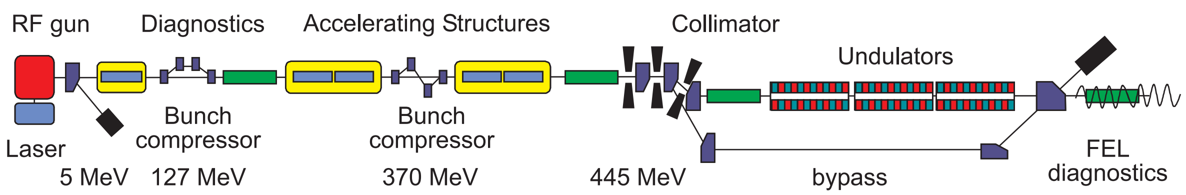

Figure 2.3.1 *Schematic layout of Phase 2 of the SASE FEL at the TTF at DESY, Hamburg, now called FLASH. The total length is approximately 330 m (including the experimental hall not shown in the sketch).*

Up to the present time (summer 2006), the maximum beam energy is limited at approximately 730 MeV, since only five TESLA Modules are installed yet, with some cavities limited in gradient.

The new tunnel built to house the additional accelerator modules, the collimator, and the undulator sections, has a circular cross section to mimic the tunnel for a future linear collider and for the X-Ray Free-Electron Laser (XFEL).

Table 2.3.1 shows a few key parameters of FLASH. It is obvious that, in spite of a factor of 1,000 difference in wavelength, the respective requirements on the electron beam invariants for the FLASH and the XFEL do not differ very much.

Item	FLASH	
Normalised emittance @ 1 nC	2π	mrad mm
Peak current	> 2500	A
Nominal bunch charge	1	nC
Maximum RF pulse repetition rate	10	Hz
Maximum RF pulse length	0.8	ms
Maximum number of bunches per RF pulse	7200	
Total length of vacuum beamlines (including bypass)	358	m
Number of magnet units (including 99 steerer magnets)	213	
Number of TESLA cavities (as of June 2006)	40	
Number of beam diagnostics units	> 146	
Total length of cables	215	km

Table 2.3.1 *Key numbers characterising the design of FLASH.*

2.3.2 Installation

As indicated in Table 2.3.1, a large number of components had to be installed into the new tunnel. During the course of this work, engineering experience was gained on the installation of SASE FEL components and superconducting accelerator components into a tunnel 5.2 m in diameter:

- Transport and installation of the TESLA Modules and the cryogenic supply lines does not represent a major problem. However, these components determine, to a large extent, the possible arrangements of other components, like klystrons, power supplies and electronics. The lessons from this experience were part of the decision to change the tunnel layout of the XFEL in terms of module mounting. The accelerator modules will be suspended from the ceiling in order to arrange all components requiring maintenance and/or replacement in a much more accessible way.
- Most of the power supplies and electronics to be located inside the tunnel were installed into 32 standard size containers with the advantage that most of the cabling work could be done outside the tunnel. In view of the XFEL, pros and cons of this concept can now be discussed based on hands-on experience. Figure 2.3.2 illustrates the location of these containers within the tunnel cross section.
- The undulator segments, each 4.5 m long, are separated by an insert containing a quadrupole doublet (mounted on micro-movers), a beam position monitor and a pair of wire scanners. These components were all mounted on a granite block and aligned, with respect to each other, to better than 50 μm precision. The overall alignment of all undulator components with respect to one another was supported, and can be monitored, by a stretched wire system.
- Klystron installation inside the tunnel will be a major issue for long accelerator tunnels (XFEL, International Linear Collider (ILC)) and was thus, originally, among the test items. Such a test was abandoned as it would have delayed the FLASH schedule considerably.

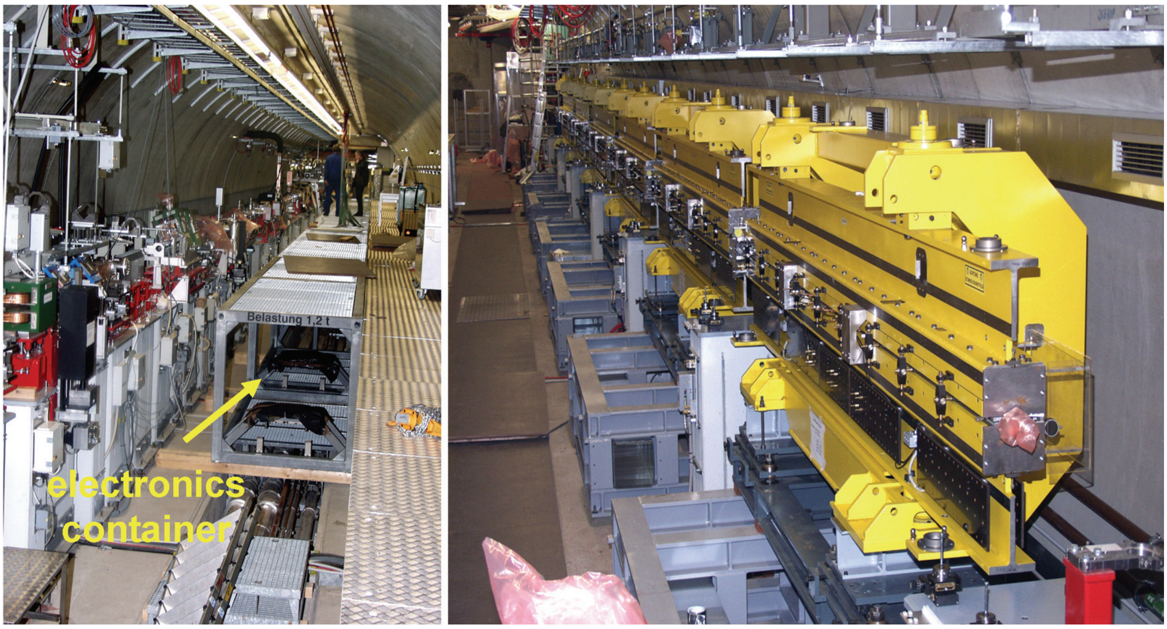

Figure 2.3.2 *Left: FLASH accelerator tunnel with part of the collimator section and an electronics container visible. Right: The undulator consists of six segments, each 4.5 m long.*

2.3.3 Accelerator commissioning

Due to the large number of different components and new as well as ambitious accelerator physics issues, initial commissioning of the machine took several months. Just after it achieved lasing close to the saturation level, first beam was delivered to the users. Even more, it was decided to start user operation without waiting to achieve full performance operation. Although this commissioning philosophy puts some burden on the early users, it seems to be adequate for a new SASE FEL, as it permits users to gain experience and perform experiments as soon as possible while the early user operation periods still allow the accelerator experts to gain knowledge about FEL physics and machine behaviour parasitically. The consequence of the chosen commissioning philosophy is, strictly speaking, that it will take several years to reach the full parameter range.

The first component setting the stage for successful FEL operation is a low-emittance electron source. A dedicated photo-injector has been developed, commissioned and characterised at the Photo-Injector Test Stand (PITZ) at DESY-Zeuthen **[2-18, 2-19]**. Having shown satisfactory performance, the gun was moved and installed into TTF, thus considerably saving commissioning time at TTF.

Commissioning of the entire beamline, some 30 m long, from the photoinjector through the first bunch compression at approximately 125 MeV was the first, major commissioning milestone. The beam dynamics of the dense electron bunch is heavily affected by space-charge forces up to (at least) 100 MeV, thus representing a serious challenge for the commissioning procedure.

The most important result of injector commissioning was the proof that the injector beamline works as theoretically predicted. For measurement of the beam emittance (see Figure 2.3.3), a periodic FODO channel was inserted, permitting a reliable and reproducible determination of beam emittance by four optical transition radiation (OTR) screens, thus eliminating the need for a quadrupole scan.

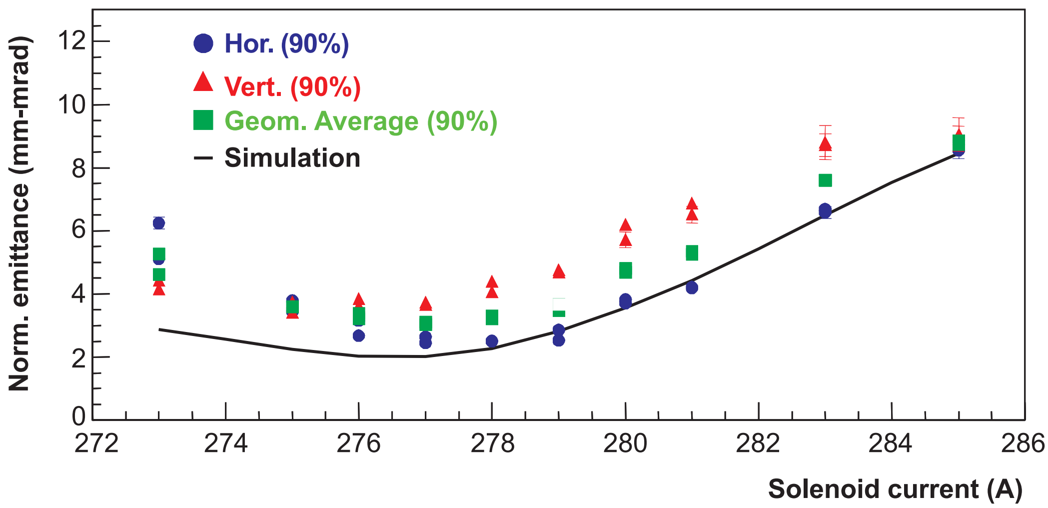

Figure 2.3.3 *Measurement of beam emittance at 125 MeV, 1 nC bunch charge, no compression, as a function of the solenoid current at the RF gun. The injector was at its nominal parameters, without further attempts to minimise the emittance. Emittance values quoted contain 90% of the bunch charge.*

When bunch compression was switched on, comparison between measured and calculated beam parameters became much harder, mainly for two reasons:

- With peak currents exceeding 1 kA, space charge forces, and coherent synchrotron radiation (CSR) effects play a leading role in beam dynamics even at beam energies above 100 MeV. According to beam dynamics simulation results, the 6-D phase-space distribution becomes very involved. The control and understanding of beam envelopes becomes very hard as they are no more determined by initial conditions and linear optics only, but also by RF phase settings and bunch charge. In addition, the generation of spurious dispersion was observed, generated, for example, by energy losses due to CSR in the bunch compressors.

- As long as a third harmonic accelerating section is missing (installation at FLASH is scheduled for 2007), the expected longitudinal electron distribution consists of a leading spike about 50 fs long, containing some 10% of the total charge with a peak current exceeding 1 kA, and a long tail with current too small for providing significant FEL gain. According to simulation, this tail has phase-space coordinates quite different from the lasing spike. As most of the diagnostics tools (like wire scanners, OTR screens or beam position monitors) are only able to determine integral properties of the bunch, it is, thus, presently almost impossible to precisely control the orbit and the optics match of the lasing spike.

In spite of these difficulties, it was, nevertheless, possible to determine important properties of the lasing spike with the help of a transverse deflecting cavity (called LOLA). In particular, it was possible to verify the expected longitudinal charge distribution, identify a horizontal offset of the spike with respect to the tail and determine the emittance of the spike. All these values are in reasonable agreement with expectations. A measurement of the longitudinal bunch shape is shown Figure 2.3.4.

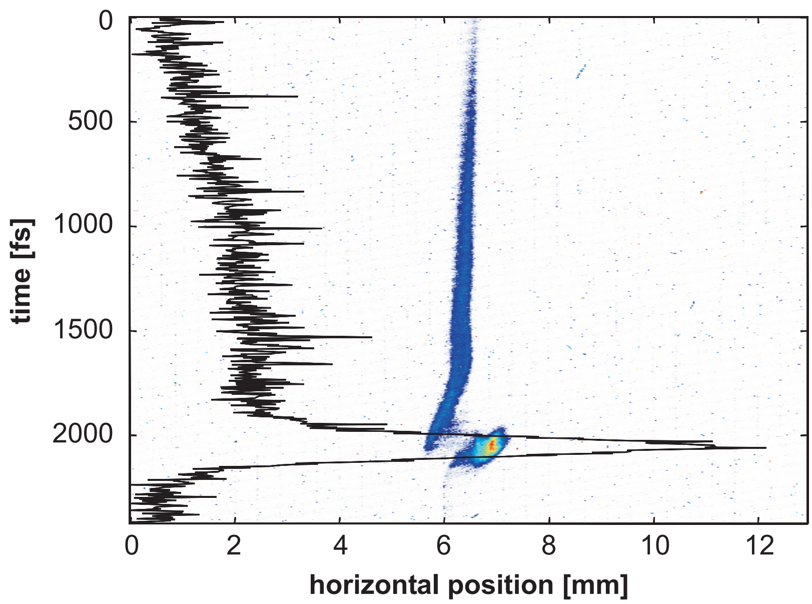

Figure 2.3.4 *Longitudinal charge distribution within a single electron bunch of FLASH. In the centre, the image of the bunch on an observation screen is seen. The screen is located downstream of a transverse mode resonator streaking the bunch vertically by a time-dependent field. The horizontal position of electrons is given on the horizontal axis, while the relative longitudinal position inside the bunch is encoded in the vertical coordinate, with the head of the bunch to the bottom. The solid curve shows the charge density projected onto the longitudinal position, i.e. the electron current profile within the bunch. A sharp spike shorter than 120 fs (FWHM) is seen at the head of the bunch, in accordance with beam dynamics calculations.*

2.3.4 FEL commissioning

Successful operation of the TTF FEL, Phase 1 in the femtosecond regime and theoretical studies **[2-17]** encouraged us to extend such a mode of operation for shorter wavelengths. It has been found that the beam formation system of the linac can be tuned for production of bunches with a high-peak-current spike driving the FEL process such that FLASH should saturate down to the shortest design wavelength of 6 nm.

Based on the experience from commissioning the TTF FEL, Phase 1 and using similar methods and tools (in particular an MCP detector), first lasing could be established at 32 nm already one week after the first passage of the electron beam through the undulator. Single shot spectra were in agreement with expectations (see Figure 2.3.5), and, at higher

FEL gain approaching the expected saturation regime **[2-20]**, second and third harmonics were observed, as theoretically expected, see Figure 2.3.6.

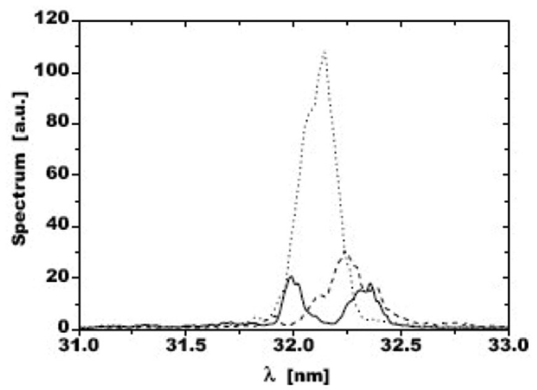

Figure 2.3.5 *Three different measured (left) and calculated (right) single-shot spectra of FLASH.*

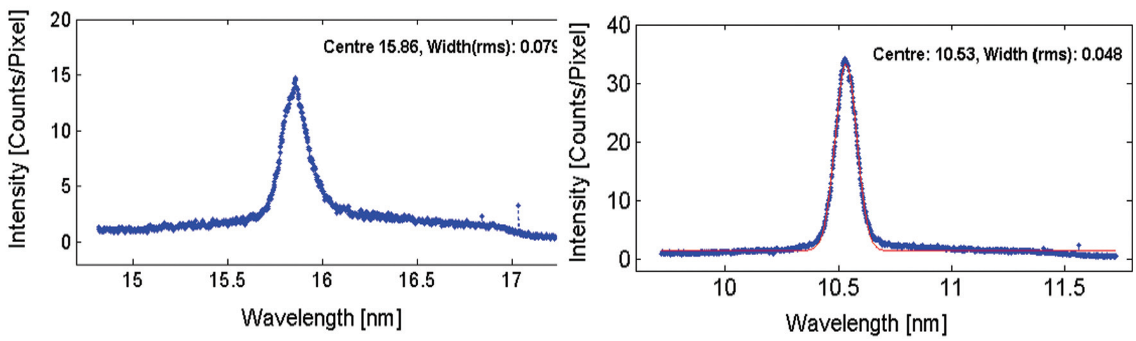

Figure 2.3.6 *Second (left) and third (right) harmonics FEL radiation spectra measured at the FLASH facility* **[2-22]**.

From the analysis of single-shot spectra and their fluctuation properties, the FWHM pulse duration of the radiation pulses has been determined at (25 ± 5) fs. The angular divergence of the radiation is almost diffraction limited **[2-20]**. Measurements of the double-slit diffraction patterns indicate a high degree of transverse coherence as well, see Figure 2.3.7. Later on, lasing has been demonstrated in the range of wavelengths from 13.1 nm to 45 nm. The best performance of FLASH has been obtained at the end of the user run in June 2006. At the wavelength of 25.7 nm, the average energy in the radiation pulse was 65 µJ, and peak values were up to 120 µJ (see Figure 2.3.8). At a wavelength of 13.9 nm, the average energy in the radiation pulse was up to 25 µJ. The peak brilliance was 1.5×10^{29} and 5×10^{29} photons/(s mrad^2 mm^2 (0.1% bandwidth)) for the wavelengths 25.7 and 13.9 nm, respectively (see Figure 1.2.2), with the accumulated uncertainty being some factor of two. We can conclude that the design goals for the present machine configuration are reached in two key aspects, namely the minimum wavelength (within the limit presently determined by the maximum energy of the accelerator) and the maximum output power: FLASH currently produces GW-level, laser-like VUV radiation pulses on a sub-50 fs scale in agreement with theoretical predictions **[2-17, 2-21]**.

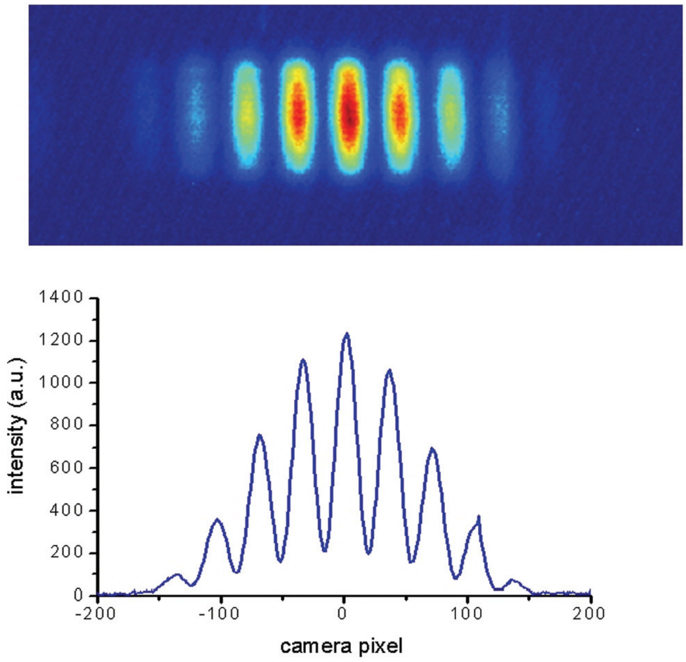

Figure 2.3.7 *Double-slit diffraction pattern taken at 25.5 nm. The large modulation depth indicates a considerable level of transverse coherence (unpublished, preliminary data).*

During FEL commissioning, two main difficulties showed up that may have some significance for the XFEL.

Beam orbit inside the undulator

All the efforts made on careful alignment and installation of the undulator did not prevent severe difficulties in establishing a straight electron orbit in the undulator. On one hand, this is due to delayed delivery and insufficient performance of beam position monitors. On the other hand, significant dipole deflections of the electron beam in the undulator section have been observed that cannot be attributed to quadrupole misalignments.

Two sources of such kind of distortions have been identified so far, namely hysteresis dipole field components in the quadrupole magnets and a magnetic stray field generated by uncompensated current leads of PETRA, the latter being a small, though inconvenient, distortion as it depends on the operation status of PETRA and is, thus, time-dependent. However, even after compensation for these effects, dipole deflections of unknown origin are observed. Of course, empirical orbit correction is done but it leaves some ambiguity in the most appropriate procedure in terms of optimising FEL gain. Part of this problem is the fact (mentioned already) that the orbit of the lasing spike does not coincide with the orbit of the total bunch charge.

Another observation that may be related, at least partially, to the orbit issue is the fact that FLASH does not yet routinely reach the ultimate performance in terms of pulse energy.

Collimation and beam losses in the undulator

In spite of the presence of a more refined collimator section, it was very difficult to keep beam losses in the undulator below an acceptable limit. Further steps were taken to remove halo particles from the beam: dark current generated in the RF gun was removed as early as possible, namely by a collimator iris at the exit of the RF gun, by a scraper in the dispersive part of the first bunch compressor, and by a fast kicker, thus removing approximately 70% of particles out of phase with the design beam. Nevertheless, wire scanner measurements in the undulator show very broad beam profiles, much wider than consistent with lasing parameters. As mentioned above, such behaviour is expected from space charge effects on beam dynamics, but at FLASH it is very likely that it is further increased by spurious dispersion generated earlier in the machine. Studies on these issues are ongoing.

At any rate, if the orbit in the undulator is well aligned, the collimator system should be able to protect the undulator from all such kinds of badly steered particles, which is not the case. Also, it is obvious that, with parts of the beam covering a large fraction of the available aperture of the undulator vacuum chamber, any kind of investigation on FEL performance becomes very tricky.

Under these circumstances, a novel, glass-fibre-based system for fast radiation dosimetry was indispensable for FEL commissioning. The system consists of a number of radiation-sensitive glass fibres distributed along the undulator. It is capable of indicating amount and location of radiation dose rates every six minutes, keeping the response time of operators reasonably small. The system is backed by traditional TLDs and by a system of fast photomultiplier-based shower counters. These counters are able to resolve individual bunches and allow distinction between beam-induced and dark-current-induced losses.

It is important to note that often perfect FEL user operation conditions were realised at FLASH, with beam losses and radiation dose in the undulator so low that full bunch train operation would be possible. However, these conditions were not sufficiently stable, so that with the machine protection system being in a rudimentary state, running FLASH at its design bunch rate is excluded up to now. It is very likely though, that more studies on beam dynamics and optics will solve the problem. The automatic machine protection system required for operation with long bunch trains is being commissioned. It also includes warning indicators and alarms in case of high losses in the undulators.

2.3.5 Experience from the first user operation periods

First user runs were scheduled in the middle of 2005 for wavelengths around 30 nm, just a couple of weeks after FEL gain close to the saturation regime was achieved. For the machine protection reasons mentioned already, the number of bunches per RF pulse was restricted between 1 and 30, depending on the user's request, running at a repetition rate of initially 2, now 5 Hz. The bunch-to-bunch separation time was 1 and 4 μs, again as requested by users. The properties of the photon pulses were routinely monitored in the control room, see Figure 2.3.8.

Quite often, the amount of fluctuation was consistent with the statistics inherent in the SASE process related to the start-up from noise. Under such conditions, smooth user runs were delivered as illustrated in Figure 2.3.9.

However, it also happened frequently, that fluctuations were much larger. Under such conditions, the FEL gain was extremely sensitive on fine tuning of parameters, especially on RF phases, photoinjector-laser settings, and the orbit in the undulator. One issue in this context is that, at the present time, it is not possible to restore SASE without any fine tuning of critical parameters. Even if all subsystems are fully operational, after restoring a previously successful machine setting, typically a few hours of fine tuning are needed to recover full FEL performance. This indicates that the control of some parameters is not precise enough.

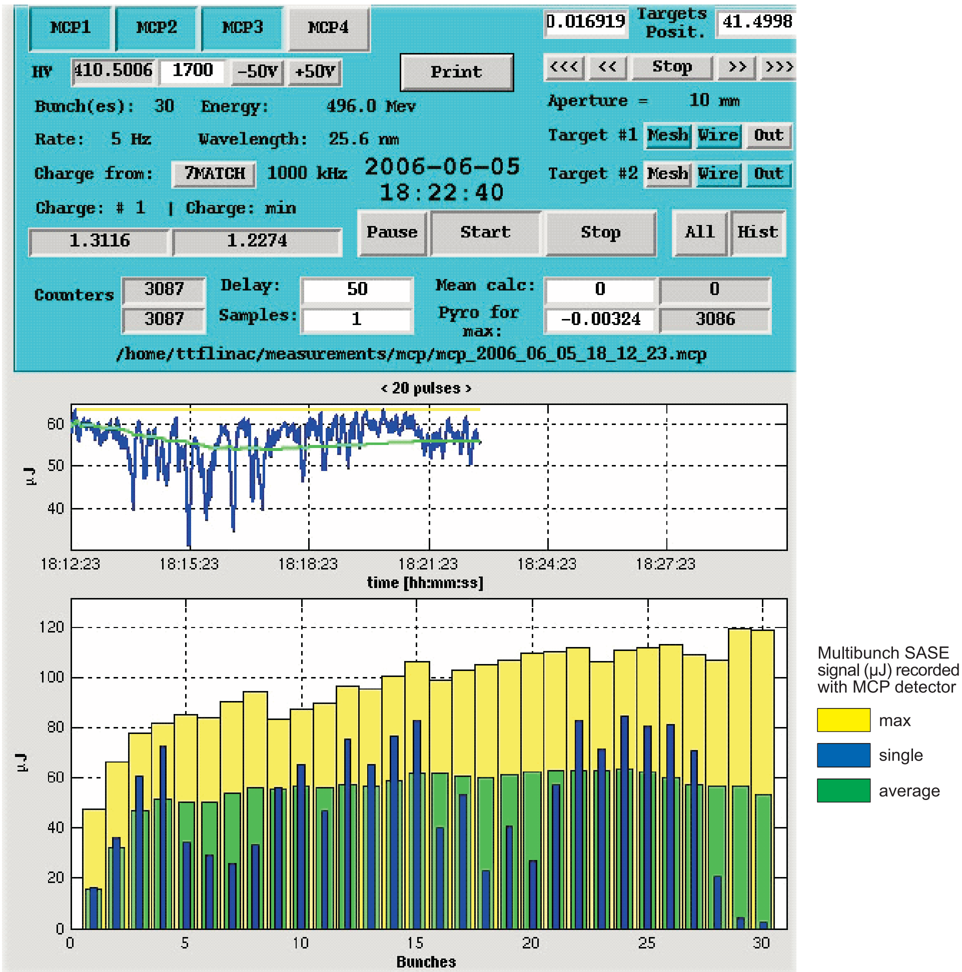

__Figure 2.3.8__ Photon pulse energies recorded at the end of the user run on 5 June 2006 (image of the control panel of the MCP detector).The radiation wavelength is 25.7 nm, and the pulse train consists of 30 bunches. For each bunch position within the train, the individual energy (blue bar), the maximum energy achieved during the measurement period (yellow bar), and the average value (green bar) are displayed in the bottom window. The window in the middle shows the temporal evolution of the mean energy averaged over all pulses contained within 20 pulse trains (blue line), and the mean energy over the entire measurement period.

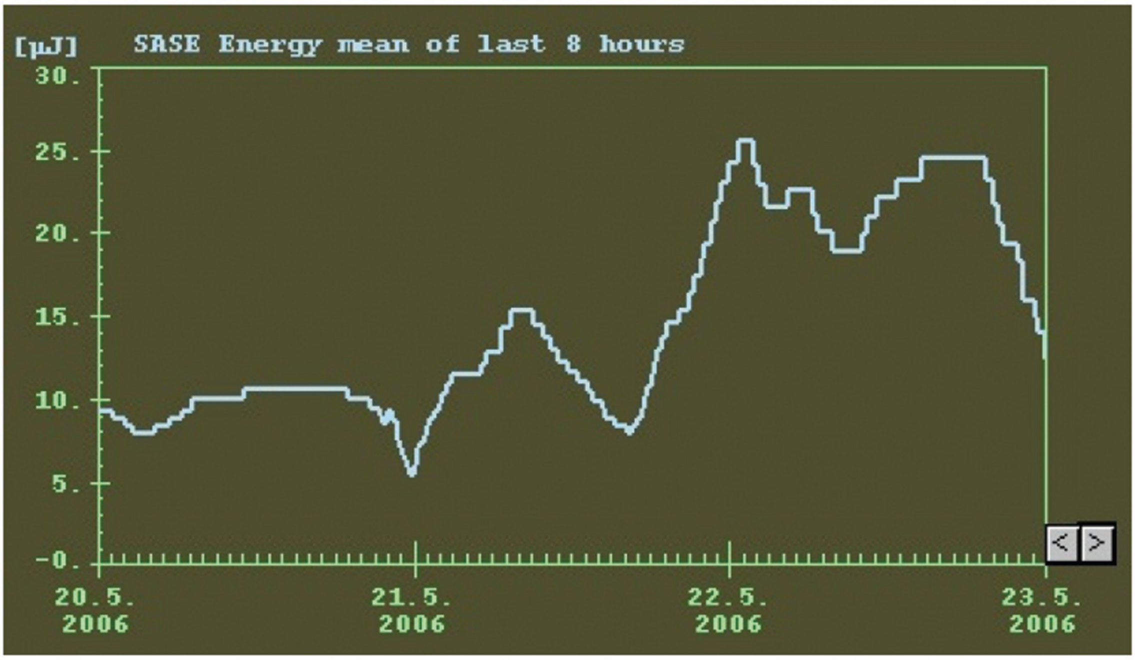

Figure 2.3.9 *Example of mean photon pulse energies (averaged over the last eight hours) recorded during three days of a SASE run at 25.6 nm wavelength. On 20-21 May. 10 μJ level of SASE has been delivered to users. On the afternoon of 21 May. SASE intensity has been retuned to the higher level by the request of the new user group.*

The FEL-beam availability during dedicated user time was, on average, over the first weeks of user operation, above 61% (see Figure 2.3.10), an acceptable level for most of the early users.

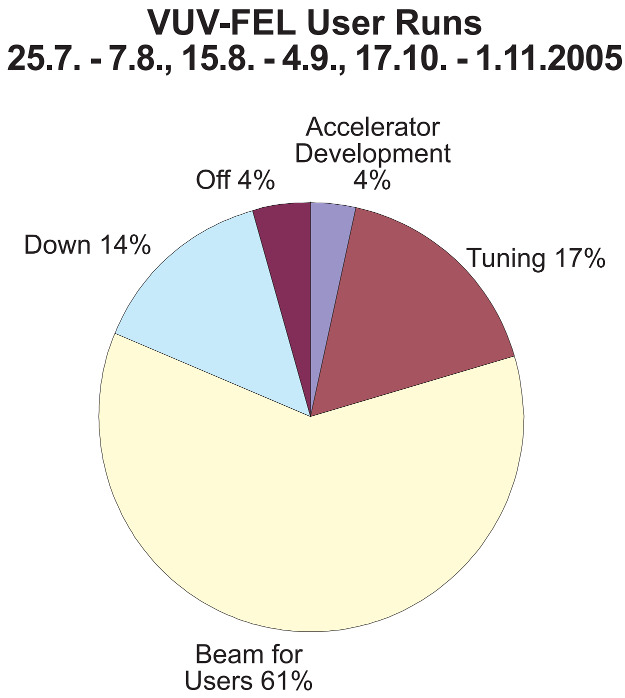

Figure 2.3.10 *Beam time availability statistics during early user operation at FLASH.*

2.3.6 Next steps for FLASH

Having established basic conditions for user operation at FLASH, a number of further steps must be taken to achieve full performance:

- a number of subsystems must be improved. For instance, the noise of power supplies for steerer magnets must be reduced, the low level RF control must be further stabilised, and the properties of the photoinjector-laser have to be improved;
- the installation of a third harmonic RF system to improve longitudinal phase-space properties of electron bunches;
- the installation of a further TESLA module to reach 1 GeV beam energy;
- the establishment of the FEL operation at wavelengths down to 6 nm (1st harmonic);
- the establishment of fast wavelength tuning. This requires, obviously, improvements in the control and reproducibility of several subsystems;
- operation with a full length of bunch trains;
- installation and commissioning of the self-seeding option at FLASH.

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