THE TTF/VUV-FEL (FLASH) AS THE PROTOTYPE FOR THE EUROPEAN XFEL PROJECT

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Abstract

The European X-ray Free-Electron laser Facility (XFEL) is going to be built in an international collaboration at the Deutsches Elektronen-Synchrotron (DESY), Germany, The Technical Design Report [1] was published recently. The official project is expected for early 2007. The new facility will offer photon beams at wavelengths as short as 1 Ångstroem with highest peak brilliance being more than 100 million times higher than present day synchrotron radiation sources. The radiation has a high degree of transverse coherence and the pulse duration is reduced from ~100 picoseconds (typ. for SR light sources) down to the ~10 femtosecond time domain. The overall layout of the XFEL will be described. This includes the envisaged operation parameters for the linear accelerator using superconducting TESLA technology. The complete design is based on the actually operated VUV free-electron laser at DESY. Experience with the operation during first long user runs will be described in detail. Various subsystems of the XFEL could be tested. Specially developed electron beam diagnostics was commissioned. A summary of the status of the XFEL preparation work will be given.

HISTORY OF THE TTF/VUV-FEL (FLASH) AND THE XFEL

The basic technology underlying the European X-ray Free-Electron Laser Facility is the superconducting linear accelerator technology, developed by an international collaboration coordinated by the DESY laboratory in Hamburg, with the initial objective to create TESLA (Tera-Electronvolt Superconducting Linear Accelerator), an electron-positron linear collider with TeV energy, for particle physics studies, hence the name TESLA technology. It was soon realized that this type of innovative linear accelerator had ideal characteristics for an X-ray free-electron laser. Proposals to build a free-electron laser, first as a side branch of the linear collider, and later as a stand-alone facility were put forward by DESY to the German government. The construction of a test facility (TESLA Test Facility 1, or TTF1) was undertaken, and lasing down to ~90 nm wavelengths was successfully demonstrated in 2000. TTF2 had the more ambitious goal to push lasing to 6 nm wavelengths, with a 1 GeV linear accelerator. This should be achieved in 2007; in the meantime, acceleration of electrons up to 0.75 GeV has obtained lasing at 32 nm (Jan. 2005) and at 13 nm (April 2006), and a vigorous user program was started in August 2005 in the experiments' hall downstream from the free-electron laser, forming what is now called the FLASH (Free-Electron Laser in Hamburg) facility. In 2003, the German government decided to launch the proposal to constitute a European Facility for the construction and operation of an x-ray free-electron laser in Hamburg, undertaking the commitment to finance the new facility by providing up to 60% of its construction costs, and up to 40% of the operation costs. The choice of the location in Hamburg is motivated by the possibility to take advantage of the unique experience and know-how of DESY in the area of superconducting linacs, and of the possibility to gain first-hand experience on the operation of an FEL through the FLASH facility.

LAYOUT OF THE XFEL FACILITY

The main components of the XFEL Facility are the injector, the linear accelerator, the beam distribution system, the undulators, the photon beamlines, and the instruments in the Experiments Hall (see Figure 1).

These components are distributed along an essentially linear geometry, 3.4 km long, starting on the DESY campus in the northwest part of the city of Hamburg, and ending in the neighbouring Federal State of Schleswig-Holstein, south of the city of Schenefeld, where the Experimental Hall is located.

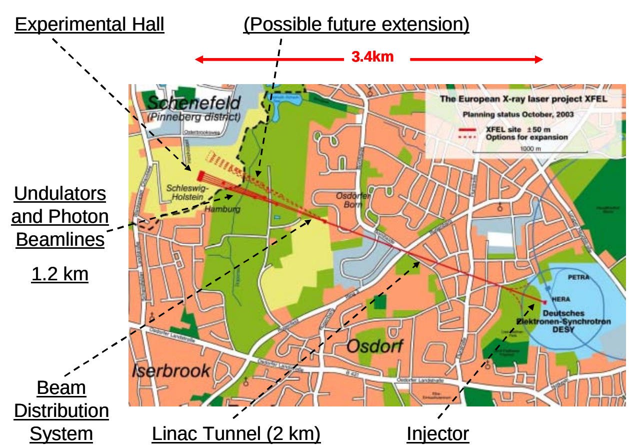

Figure 1: Schematic layout of the main components of the European XFEL Facility.

The basic functions of the main components are schematically described in the following: In the injector, electron bunches are extracted from a solid cathode by a laser beam, accelerated by an electron RF gun and directed towards the linear accelerator with an exit energy of 120 MeV. In the linear accelerator, consisting of a 1.6 km long sequence of superconducting accelerating modules, magnets for beam steering and focusing, and diagnostic equipment, the electrons are accelerated to energies of up to 20 GeV (17.5 GeV is the energy foreseen for the standard mode of operation of the XFEL facility). Along the accelerator, two stages of bunch compression are located, to produce the short and very dense electron bunches required to trigger the SASE process. At the end of the linac, the individual electron bunches are channeled down one or the other of two electron beamlines by the beam distribution system.

Different undulators allow for different photon wavelength. Figure 2 shows the projected brilliance of the XFEL as well as the already achieved peak brilliance at FLASH.

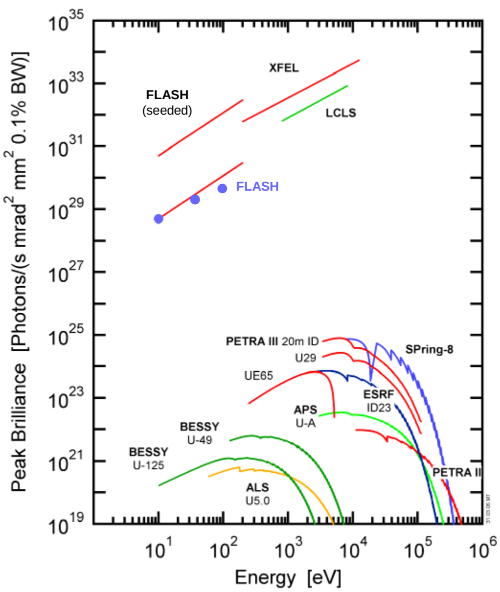

Figure 2: Peak brilliance of X-ray FELs versus 3rd generation SR light sources. Blue spots show experimental performance of the FLASH facility.

TTF/FLASH IN THE XFEL CONTEXT

In the early 90s, the work at TTF 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 [2]. 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 realized 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 small wake field effects (large iris diameter of accelerating structures), and due to the excellent power efficiency (high duty cycle) thus allowing 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 [3]. As there are no normal incidence mirrors at very short wavelengths, the Self-Amplified Spontaneous Emission (SASE) principle [4, 5] was the most promising concept to adopt.

At that time, the SASE principle was experimentally demonstrated only at wavelengths in the microwave regime. The direct jump to Ångstroem 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 [6] to reach 100 nm, a wavelength regime where the SASE FEL principle is competitive with other types of lasers.

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 of TTF, the scientifically attractive 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, and an additional bunch compressor and a 30 m long undulator had to be installed, as well as a hall for user experiments had to be built. A proposal of a two-stage realization of a SASE FEL user facility based on the TESLA Test Facility was endorsed by an international advisory committee.

Figure 3 gives the schematic layout of the TTF/VUV-FEL (FLASH) installation at DESY, Hamburg. The total length is approx. 330 m (including the experimental hall not shown in the sketch).

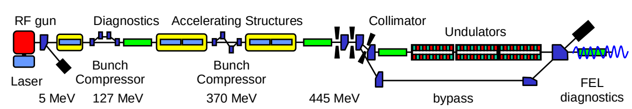

Figure 3: Schematic layout of phase 2 of the SASE FEL at the TESLA Test Facility at DESY, Hamburg, now called FLASH.

Table 1 shows a few key parameters of FLASH. In spite of a factor of thousand difference in wavelength, the respective requirements on the electron beam invariants for FLASH and the XFEL are quite similar within about a factor of two.

Table 1: Key Parameters of the FLASH Facility

Normalized 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
Number of TESLA cavities (as of June 2006)	40
Number of beam diagnostics units	~ 150

Results from TTF/VUV-FEL(FLASH) Operation

The TTF1 FEL demonstrated a unique femtosecond mode of operation which was not considered at an early design stage of the project [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 bunch compression system. Despite strong collective effects, this spike was bright enough to drive the FEL process up to saturation for wavelengths around 100 nm [7, 8, 9]. The TTF1 FEL delivering a peak brilliance of 2×10^{28} photons/(s mrad^2 mm2 (0.1% bandwidth)) between 80 and 120 nm, was readily used to perform pioneering experiments [10, 11].

A most important result was the perfect agreement between FEL theory and observation in the wavelength regime around 100 nm.

Based on the experience from commissioning the TTF phase 1 FEL, first lasing at TTF2 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, and, at higher FEL gain approaching the expected saturation regime [12], 2nd and 3rd harmonics were observed, as theoretically expected.

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 [12]. Measurements of the double-slit diffraction patterns indicate a high degree of transverse coherence as well. Later on, lasing has been demonstrated in the range of wavelengths from 13.1 nm to 45 nm. The best performance of FLASH during user operation 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 4). Recently, in dedicated FEL studies, the average energy in the radiation pulse was up to 70 µJ at 13.7 nm, with peak energy of 170 µJ. At 32 nm, 100 µJ average / 200 µJ peak were achieved. The peak brilliance was 1.5×10^{29} and well above 5×10^{29} photons/(s mrad^2 mm2 (0.1 % bandwidth)) for the wavelengths 25.7 and 13.7 nm, respectively. 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 [13, 14].

First User Operation Periods

First user runs were scheduled mid 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 above, 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 4.

The FEL-beam availability during dedicated user time was, in average over the first periods of user operation, around 60%, an acceptable level for most of the early users. At present, blocks of three weeks of FEL studies are followed by four week long dedicated user operation period (24 hours, 7 days a week).

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

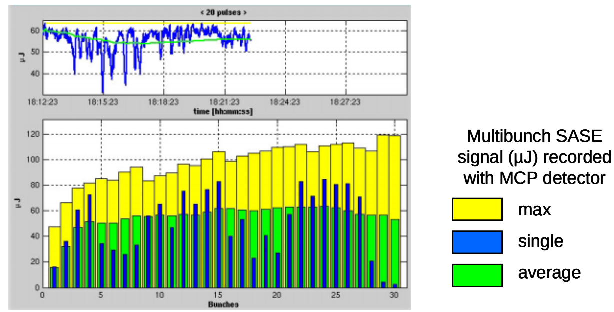

Figure 4: Photon pulse energies. The radiation wavelength is 25.7 nm, and the pulse train consists of 30 bunches. For each bunch position within the train, the individual energy (blue), the maximum energy achieved during the measurement period (yellow), and the average value (green) are displayed in a bottom window.

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 beam trajectory in the undulator. SASE operation still requires fine tuning of critical parameters. Even if all subsystems are fully operational, after restoring a previously successful machine setting, typically a few hours of such fine tuning are needed to recover full FEL performance. This indicates that the control of some parameters is not precise enough.

Having established basic conditions for user operation at FLASH, a number of further steps had to be taken to achieve full performance, including further improvement of a number of subsystems (e.g. steerer power supplies, the low level RF control, and the photoinjector-laser).

Installation of a 3rd harmonic RF system will improve the longitudinal phase space properties of electron bunches while installation of a further TESLA module will allow an electron beam energy of 1 GeV. Finally FEL operation at wavelengths down to 6 nm (1st harmonic) can be established. At present, fast wavelength tuning is under preparation. This requires, obviously, improvements on the controls and reproducibility of several subsystems. Operation with full length of bunch trains was started and is scheduled for user operation for fall 2006.

XFEL ACCELERATOR COMPLEX

The layout of the accelerator is schematically shown in Figure 5. The electron beam is generated in a laser-driven photocathode RF gun and pre-accelerated in a single superconducting accelerator module. The injector is housed in an underground enclosure separate from the linac tunnel, so that it can be commissioned at an early stage, well before installation work in the linac tunnel is completed. Furthermore, there is space foreseen for a completely separate and radiation-shielded second injector, which can be constructed, commissioned and maintained independently from the operation of the first injector.

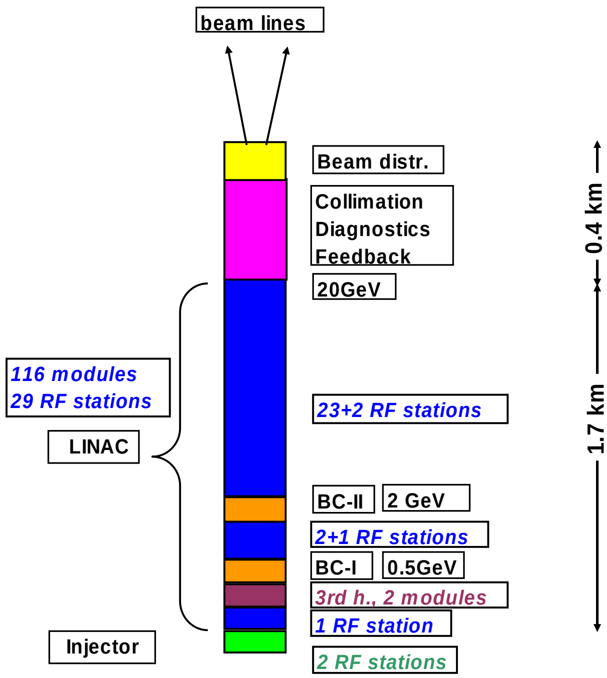

Figure 5: Schematic layout of the accelerator.

After transfer to the main accelerator tunnel, the beam is further accelerated by one linac unit (4 accelerator modules with 8 cavities each, driven by one RF station) to an energy of 0.5 GeV before entering the first bunch compression stage. A third harmonic (3.9 GHz) RF system is foreseen to optimize the longitudinal phase space properties. After acceleration to 2 GeV with three linac units the beam enters the second (final) compression stage, after which the bunch peak current has increased to 5 kA, a factor of 100 higher than the initial peak current from the RF gun. Considerable attention has been paid to foresee extensive standard and special beam diagnostics tools in order to assess the beam phase space properties after the compression process in great detail.

Final acceleration to a nominal maximum beam energy of 20 GeV takes place in the main part of the linac, consisting of 25 RF stations and 100 accelerator modules in total. Downstream from the linac follows a conventional beam line for installation of the beam collimation and trajectory feedback systems, as well as providing distribution of the beam into the different undulator beam lines, including the connection to a future upgrade of the user facility with more beam lines. A combination of slow and fast switching devices permits to generate bunch trains of different time patterns for different experiments without having to generate and accelerate bunch trains with strongly varying transient beam loading in the linac. After having passed through the undulators, the “spent” beam is stopped in radiation shielded solid absorbers. An additional beam dump is installed in the beam distribution shaft XS1, just upstream from the undulator beam lines. It allows to commission or to operate the accelerator while installation or maintenance work is ongoing in the undulator tunnels.

The layout of the linac includes precautions for energy management in case of RF component failure. The section between the two bunch compression stages consists of three RF units with four accelerator modules each, out of which only two have to be active to accelerate the beam to 2 GeV at the design gradient. Likewise, the main section of the linac (from 2 to 20 GeV) has an overhead of two RF stations. This guarantees that in case of an RF unit failure there is sufficient energy reserve to maintain both the beam energy at the second bunch compressor stage as well as at the end of the linac. Tunnel access for repair of RF stations during scheduled operation time can thus be safely avoided. In practice, the reserve stations will not be left idle when not needed. Instead, all available stations will be operated with reduced gradient and in case a station fails the gradient will be increased in the other sections such as to keep the beam energy constant.

The main parameters of the accelerator are summarized in Table 2. The beam energy required for 0.1 nm photon wavelength in the SASE1 and SASE2 beam lines is 17.5 GeV. The linac design energy of 20 GeV thus already includes the potential to reach a lower wavelength of about 0.08 nm. The required peak power per RF station is well below the limit of the 10 MW multibeam klystrons. This de-rated mode is beneficial for highly reliable operation on one hand and for an upgrade potential regarding beam energy or duty cycle on the other. Likewise, the cryogenic system is laid out with an overhead of 50% with similar operational benefits.

Table 2: Main Parameters of the XFEL Accelerator

Energy for 0.1 nm wavelength	17.5 GeV
(max. design energy)	*(20 GeV)*
# of installed accelerator modules	116
# of cavities	928
Acc. Gradient (104 act. mod.) at 20 GeV	23.6 MV/m
# of installed RF stations	29
Klystron peak power (26 active stations)	5.2 MW
Loaded quality factor Q_{ext}	4.6×10^6
RF pulse length	1.4 ms
Beam pulse length	0.65ms
Repetition rate	10 Hz
Max. average Beam power	600 kW
Unloaded cavity quality factor Q_0	10^{10}
2K cryo load (incl. transfer line losses)	1.7 kW
Max. # of bunches per pulse *(at 20 GeV)*	3,250 *(3,000)*
Min. bunch spacing	200 ns
Bunch charge	1 nC
Bunch peak current	5 kA
Emittance (slice) at undulator	1.4 mm×mrad
Energy spread (slice) at undulator	1 MeV

Operational Flexibility

The single set of basic reference parameters in Table 2 does not cover the full range of operational flexibility of the linac. There is, within certain limits, a considerable flexibility regarding operation parameters, based on built-in performance reserves of its technical components. Operation at lower beam energy, thus extending the photon wavelength range to softer X-rays, is an obvious possibility. On the other hand, based on the experience gained with the superconducting TESLA cavities, it can be realistically expected that the linac can be operated at an accelerating gradient somewhat above the specified design value of 23.6 MV/m at 20 GeV. An increase of the gradient to about 28 MV/m would permit a maximum beam energy of 24 GeV, thus significantly extending the photon wavelength range to harder X-rays, provided that simultaneously also an improved injector beam quality becomes available to be able to maintain saturation of the SASE FEL process. In addition to the possibility of higher beam energies, the available reserve in the RF and cryogenic systems can also be used for increasing the linac repetition rate and thus the duty cycle of the pulsed linac. At sufficiently low beam energy, a 100% duty cycle, i.e. continuous wave (CW), mode of operation is conceivable, an option which is only possible with a superconducting linac. This option is viewed as not being part of the first stage of the XFEL facility but is considered as a future option.

SYNERGY OF XFEL AND ILC R&D

There is a clear synergy between the XFEL project and the actual ILC R&D efforts. Figure 6 tries to emphasize the importance of the XFEL for the ILC. The current preparation phase – aiming at the project start early 2007 – includes the industrialization of all linac sub-systems. The following production phase will clearly include acceptance tests of all accelerator sections. Around 2010, when results from the major ILC R&D projects are expected and the conversion to a possible pre-construction phase could be started, experience from the XFEL series production is on hand.

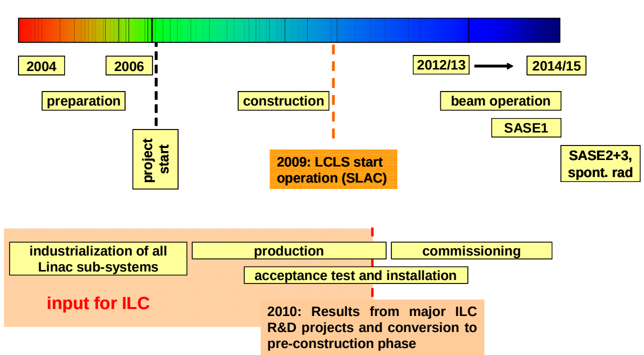

Figure 6: XFEL time schedule vs. ILC R&D efforts.

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