STATUS OF THE TTF FEL

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Abstract

The free electron laser at the TESLA Test Facility at DESY (TTF-FEL) is now being extended to lase with shorter wavelengths from the VUV to the soft X-ray regime, serving a broad spectrum of users. Additional superconducting accelerating modules of the TESLA type have been installed recently. In their final stage, they will boost the electron beam energy up to 1 GeV, permitting lasing at a wavelength of 6 nm. Further upgrades for instance in the injector will enhance the beam quality required for short wavelengths. A description and the status of the project is given.

INTRODUCTION

The TESLA collaboration has at present three major projects: the TESLA linear collider [1], the XFEL [2], and the VUV-FEL (TTF-FEL) [3, 4, 5]. The TESLA linear collider is one of the competitors for the next large accelerator facility for high energy physics: an e^+e^- linear collider using the TESLA superconducting acceleration technique. The XFEL project is the core of a proposal for a European Laboratory of Excellence for fundamental and applied research with ultra-bright and coherent X-ray photons. The XFEL will be based on TESLA technology. The VUV-FEL (or TTF-FEL Phase 2) under construction at the TESLA Test Facility (TTF) at DESY will be the first user facility for VUV and soft X-ray coherent light experiments with impressive peak and average brilliance. It is a piloting facility for the XFEL project and serves as a test facility for further TESLA linear collider related research and development.

Not all aspects of the TTF-FEL can be covered in this report, emphasis is therefore put on subjects related to this workshop: the superconducting acceleration structures.

TTF PHASE 1

The TTF linac phase 1 has been a great success in demonstrating the feasibility and operability of superconducting accelerating structures with TESLA design [6]. Moreover, it has been used to drive the first SASE-FEL at wavelengths in the range of 120 to 80 nm [7, 8, 9].

Third Generation of Accelerating Modules

A TESLA accelerating module has a length of 12 m and includes eight 9-cell superconducting cavities (1.038 m active length) and a quadrupole/steerer/BPM package. The static losses are 1.5 W at 2 K.

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Over the last years, the design has been improved to meet the TESLA requirements in performance and cost [10]. Examples of improvements are a reduction of the diameter of the vacuum vessel to a standard 38" pipe, finger welded shields, higher stability in quadrupole positioning during pumping and cool-down and a simplified alignment strategy. Sliding fixtures holding the cavities allow adjustments to the rigid positioned couplers, and keep cavities aligned during cool-down. From the new third generation modules three have been assembled so far. In April 2003 two of them have already been installed in the linac (modules 4 and 5). Figure 1 shows a third generation TESLA acceleration module during assembly at TTF.

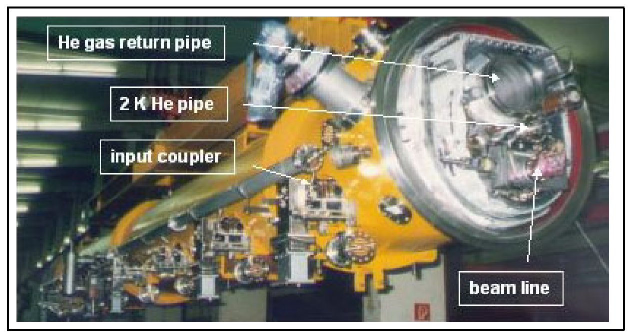

Figure 1: Third generation TESLA superconducting acceleration module during assembly.

Performance of Modules

Several modules have been tested in the TTF linac, with and without beam. Figure 2 shows the measured average gradient achieved during these tests. The gradients are given at 2 K for an unloaded Q of $1{\cdot}10^{10}$ and $5{\cdot}10^9$. The module data are compared to the average gradient obtained from the results of the single cavity tests in a bath cryostat (vertical test).

The module numbers follow the date of assembly: module 1 has been assembled in Oct. 1997, module 5 in March 2002 (see Table 1). Modules indicated by a star (*) are reassembled modules, where cavities with lower performance have been exchanged.

With the assembly of five modules and the reassembly of three others, a clear trend to a performance is visible, which meets now the TESLA 500 specification: 23.4 MV/m with a $Q > 5{\cdot}10^9$. The progress is mainly due to an improved welding technique [11] and stricter Niobium quality control [12]. For details on the cavity treatment refer to [13].

Most of the cavities have – on average – a similar performance in the module than in the bath cryostat. However,

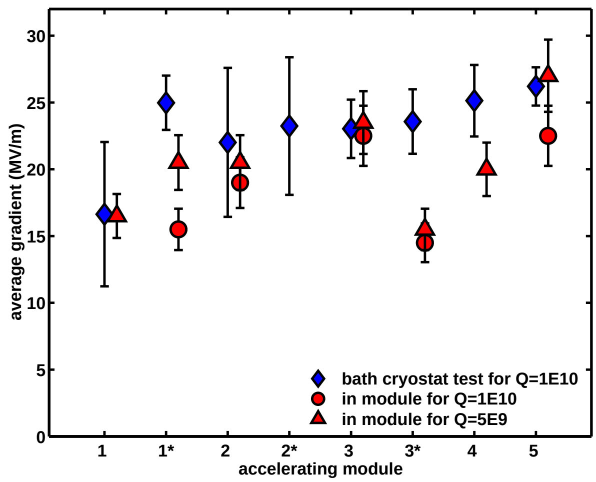

Figure 2: Average gradient of modules installed in the TTF linac. Red circles indicate the measured gradient at 2 K for a Q of $1{\cdot}10^{10}$, the red triangles for a Q of $5{\cdot}10^{9}$. The data are compared to the average gradient obtained from results of the single cavity tests in a bath cryostat prior to assembly into the module, also for 2 K and a Q of $1{\cdot}10^{10}$ (blue diamonds). The error bars for the module gradient is the measurement error, for the single cavity tests the rms of the individual results. The data are listed in Table 1.

single cavities or single couplers show problems after installation and lead to a reduction of the average gradient. This is especially the case for module $3^\star$. Because one coupler had an accidentally closed valve, one cavity could not been tested. Excluding it, 18 MV/m have been reached. This module also suffered from problems in the assembly procedure of the warm parts of the couplers, which explained the unsatisfactory performance of the tested cavities. Six cavities in module 5 and three in module 4 reached 30 MV/m with very small cryogenic losses ($\ll$ 1 W, 1 Hz operation). Four cavities in module 4 reached 24 MV/m, the average gradient is low due to one coupler, whose conditioning could not be completed in time. The RF tests of all modules will be continued during the commissioning of TTF phase 2, together with module $2^\star$, which will be installed in January 2004 (Fig. 4). Improvements for modules $3^\star$ and 4 are likely.

Table 1 summarizes the results.

During TTF phase 1, several running periods have been devoted to operate modules with full TESLA beam loading. From this running experience, we conclude, that the maximal achievable gradient of a module is not due to structural damage, but rather determined by a low Q, high field emission, or quench. It is not a hard limit, approaching the limit results in higher cryogenic load, radiation, and dark-current. Reducing the gradient always recovers stable operating conditions, which is in general a few percent below the first quench.

The low level RF system regulates the vector sum of all eight cavities in a module [14]. In the case of a quench in

Table 1: Measured average gradient of modules at TTF. The gradients are given for an unloaded Q of $1{\cdot}10^{10}$ (a) and $5{\cdot}10^{9}$ (b). The error of the measurement is about 10 %. The vertical tests are with individual cavities in a bath cryostat: here, the average gradient is calculated with all cavities installed in a given module at $Q = 1{\cdot}10^{10}$) – together with the rms spread of the individual results. All data are at 2 K, units in MV/m. Assembly and installation date are included. (These Data are plotted in Fig. 2).

No.	**Assembly date**	**Inst. date**	**Vert. test** (a)	**rms**	**Module test** (a)	(b)
1	10/97	11/97	16.6	5.4		16.7
$1^\star$	02/00	06/02	25.0	2.0	15.5	20.5
2	09/98	09/98	22.0	5.6	19.0	20.5
$2^\star$	12/03	01/04	23.2	5.1	–	–
3	04/99	06/99	23.0	2.2	22.5	23.5
$3^\star$	02/03	04/03	23.6	2.4	14.5	15.5
4	07/01	04/03	25.1	2.7		20
5	03/02	04/03	26.2	1.4	22.5	27

one cavity the feedback system would increase the gradient in others and thus could lead to a chain of subsequent quenches. A system to early detect quenches avoids this.

Further improvement in gradient has been achieved using the electro-polishing technique. Fully assembled electro-polished 9-cell TESLA cavities have been operated for more than 1100 h in the TTF test cryostat with a gradient of 35 MV/m with a Q close to $1{\cdot}10^{10}$ [15].

Beam Experiments with Superstructures

A promising option of the TESLA technology is to combine to 9-cell cavities to form a weakly coupled superstructure. This scheme would reduce the number of required power couplers and associated waveguides by a factor of 2. To test the structure with beam, two superstructures of two 7-cell TESLA type cavities have been assembled into a standard cryostat and installed into the TTF linac. During summer 2002, several successful experiments have been performed [16]. For instance, beam loading requires a constant refilling of energy into the structures to keep the energy spread of a TESLA bunch train small. Despite the weak coupling between the two structures, refilling could be successfully demonstrated. The energy spread measured after acceleration was well below $5{\cdot}10^{-4}$, meeting the design goal for TESLA.

In the past, higher order dipole modes have been a concern. Measurement of these modes with and without beam showed, that dipole modes $<$2.6 GHz are damped by a factor of 5 to 100 better than required.

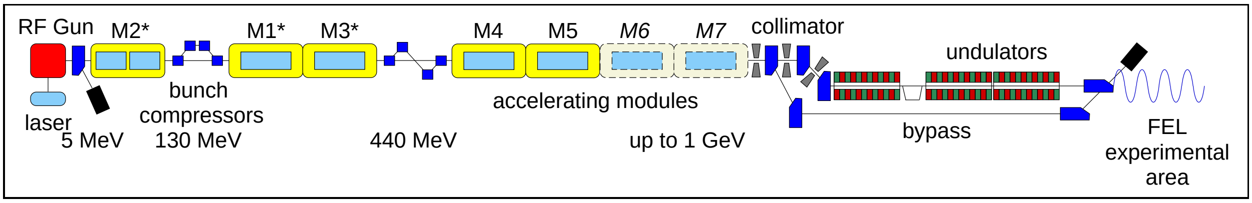

Figure 3: Schematic overview of the TTF linac phase 2 (not to scale). Beam direction is from left to right, the total length is 250 m.

FEL Experiments

Beside the successful tests of superconducting accelerating modules, the TTF linac has been used to drive a SASE free electron laser. Saturation has been achieved in Sept. 2001 at a wavelength of 98.1 nm [7]. The proof-of-principle of the VUV SASE FEL process was a major step towards the on-going extension of TTF phase 2 and and the planing of other FEL projects worldwide.

In order to test the feasibility of the machine as a user facility, two pilot experiments using the FEL radiation have been set-up. The overall satisfactory performance of the machine in the FEL mode lead to out-standing results in the atomic cluster [17] and ablation experiment [18].

TTF has been operated around the clock and accumulated 15,000 h of beam time since 1997. In a typical week, the accelerator delivered beam to the users in 63 % of the time, 19 % has been tuning, 8 % have been down time. The up-time for FEL users or accelerator studies in 2002 has been 55 %, the beam up-time close to 90 %. This has certainly to be improved, but shows already now the feasibility of the TTF FEL as a user facility.

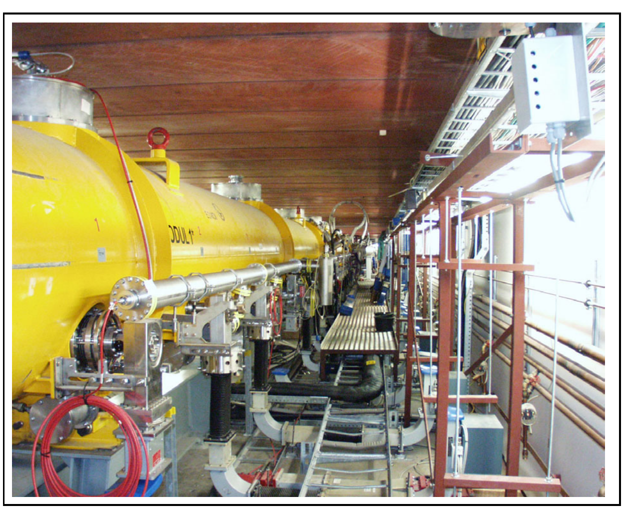

Figure 4: Superconducting TESLA modules installed in the TTF linac during installation of the waveguides.

TTF PHASE 2

The goal of phase 2 is to provide a user facility for FEL radiation from the VUV (120 nm) to the soft X-ray wavelength range (6 nm).

It is a pilot facility for a future XFEL based on TESLA technologies and a test bed for further research and development for linear collider related superconducting accelerator technologies.

Figure 3 gives a schematic overview of the linac under construction. Table 2 summarizes the main beam parameters of the TTF phase 2 linac and some expected FEL properties. For a more detailed discussion of parameter choices refer to [3].

Table 2: Design parameters of the VUV-FEL at TTF (Phase 2) (from [3]).

Electron beam		
Energy	MeV	1000
Peak current	kA	2.5
Emittance, norm. (x,y)	μm rad	2
Bunch length	μm	50
Nb. of bunches/train		7200
bunch train length	ms	0.8
Rep. rate	Hz	10
ΔE/E (rms)	%	0.1
Undulator		
Period	cm	2.73
Gap	mm	12
Peak magnetic Field	T	0.495
FEL radiation		
Wavelength	nm	6
Peak Power	GW	2.8
Bandwidth (fwhh)	%	0.36
Pulse duration (fwhh)	fs	200
Peak spectral Brilliance	B *	$2.4{\cdot}10^{30}$

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

For the start-up phase in 2004, emphasis is on achieving lasing and saturation at a wavelength of 30 nm, which requires a beam energy of 461.5 MeV. Later, lasing at longer and shorter wavelength and finally down to 6 nm will follow.

The machine design of phase 2 follows the experience made with the TTF phase 1 (see TTF CDR [19]). In the following, some important upgrades will be discussed.

Accelerating Modules

Since the obtainable wavelength is a function of the beam energy, the TTF linac is currently upgraded to deliver a beam energy of up to 1 GeV. From 2004 on, the linac will be operated with five TESLA accelerating modules (modules $2^\star$, $1^\star$, $3^\star$, 4, and 5). From their performance as given in the previous section, the energy delivered will be up to 800 MeV, largely sufficient to perform the first steps, lasing at 30 nm and below. A sixth module is in preparation to boost the energy to 1 GeV. In addition, space is reserved for a seventh module, which could be a 17 m long prototype of a compact TESLA module of twelve 9-cell cavities (see [1]).

Injector

One of the main improvements is the upgrade of the injector, which follows the proposal for the XFEL [20].

As in phase 1, a laser-driven photocathode warm RF gun generates electron bunches with a charge of 1 nC each. The normalized transverse emittance is expected to be less than 2 μm. It will be obtained by choosing a long and longitudinal flat-hat laser pulse, leading to a long initial bunch length of 2.2 mm. With this, space charge induced emittance growth is reduced.

The initial goal of generating a short bunch with at the same time small emittance has not been possible with the phase 1 scheme, where the first bunch compression took place at a low energy, 15 MeV, the second at 100 MeV. Originally, the phase 1 injector has been designed for linear collider studies, and could hardly meet FEL specifications. Nevertheless, the SASE FEL has been operated with this set-up by keeping the bunches long (3 to 4 mm) and by a proper use of the RF induced curvature in the energy-phase plane to generate a sharp high peak current spike in the kA range with the second compressor [21].

A new RF gun (Fig. 5) and an upgraded laser system have been successfully tested at PITZ [23]. The new gun has a negligible breakdown rate; the upgraded laser has a better stability and improved flat-hat laser profile (transverse and longitudinal). Especially the use of a longitudinal flat-hat profile (gaussian at phase 1), improves the transverse emittance significantly. Recent measurements indicate, that the design goal in transverse emittance is met. Installation of the RF gun is foreseen in January 2004.

To further stabilize the small emittance during acceleration, the phase 1 booster cavity with one 9-cell structure is replaced by module $2\star$. Its first four cavities are used as a booster with moderate gradient (12 MV/m), which avoids too strong focusing by the ponderomotive force during acceleration. The last four cavities are used for further acceleration with full gradient.

The bunch is then compressed down to 50 μm by magnetic chicane compressors in two stages at higher energies than before (130 MeV and 440 MeV). A two stage scheme compromises a compression at low energy to reduce the RF curvature effect, and at high energy to reduce space charge effects. New is the use of a superconducting third harmonic cavity (3.9 GHz) before the first bunch compression to compensate for the RF induced curvature in the energy plane [22]. This cavity will not be available for the initial run next year. Therefore, the strategy to drive the FEL will still follow the phase 1 scheme as described above.

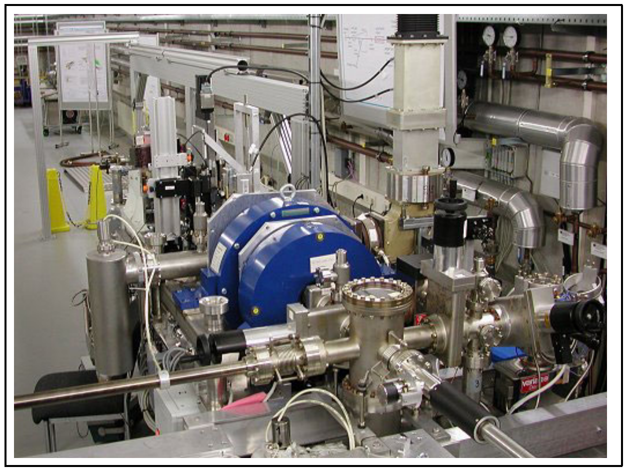

Figure 5: RF gun during the tests at PITZ in DESY-Zeuthen. In the front the cathode load lock system. The RF gun is inside the solenoids (blue).

Other Improvements

The collimation section is to protect the undulators from radiation due to off-energy and off-orbit particles. The design included now a collimation in the energy phase space as well. It integrates a fast orbit feedback system and matches the beam to the undulator entrance [24].

The beam imaging system is based – as in phase 1 – on optical transition radiators (OTR). Twenty-four stations with movable radiators are being installed, equipped with a significantly improved high resolution imaging system each, based on digital cameras [25].

A new method of measuring the bunch length uses a deflecting cavity (S-band, length 3.64 m) in combination with an OTR beam size monitor. The cavity, klystron, and modulator have been installed in fall 2003 and are being conditioned now [26]. The expected resolution of the system is in the order of 20 μm.

The undulator system is extended from three modules to six modules, now without internal focussing [27]. The total length is 27.3 m. The fixed gap is 12 mm with a peak magnetic field of 0.47 T (K=1.17). It is designed for the complete wavelength reach of 120 to 6 nm. Later, additional equipment and undulators will be added for the seedings scheme to provide fully coherent radiation [28].

The FEL experimental hall will be equipped with five experimental stations, including a laser system for pump and probe experiments, serving a variety of experiments in basic and applied research of multiple scientific fields, from life science, chemistry to physics.

Outlook

Major parts of the installation of phase two is being finished now. First beam in the injection section is expected early 2004, beam up to the beam dump in summer 2004. First lasing of the FEL at 30 nm and – hopefully – achieving saturation will follow before the end of 2004. The start of the TTF FEL as a user facility in foreseen for 2005.

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