THE TESLA FREE ELECTRON LASER – CONCEPT AND STATUS

J . Rossbach, for the TESLA FEL Collaboration
Deutsches Elektronen-Synchrotron, DESY, 22603 Hamburg, Germany

Abstract

The aim of the TESLA Free Electron Laser (FEL) is to develop and realize an Angstrom wavelength, high gain FEL in parallel with the TESLA superconducting e+/e- linear collider. As a first step, an FEL for the VUV wavelength regime is now under construction at DESY, making use of the TESLA Test Facility (TTF).

The VUV FEL at the TTF comes in two phases, which are both approved. The paper describes the over-all layout of each phase and the status of components.

1 FREE ELECTRON LASERS FOR SHORT WAVELENGTH

Over the past 30 years, synchrotron radiation has turned into a most powerful research tool that has been applied in many fields of science ranging from physics, chemistry and biology to material sciences, geophysics, and medical diagnostics. This rapid progress was driven by the development of new, increasingly brilliant sources based on electron storage rings. Due to the recent progress in accelerator technology the possibility has been opened up to complement storage ring based sources by ultra-brilliant Free-Electron Lasers operating in the soft X-ray regime.

In a Free Electron Laser (FEL), an electron beam radiates photons at much higher power and better coherence than it does due to spontaneous synchrotron radiation. The key point is that electrons moving in a transverse magnetic field of alternating polarity (undulator) may amplify an existing electromagnetic radiation field (see e.g. [1]). For properly chosen phase and wavelength (see eq. 1) the scalar product of the electron's velocity vector and the electric field vector does not vanish on average, resulting in an average energy transfer between the electron beam and the radiation field. As a consequence of this interaction, depending on the relative phase, some electrons get accelerated and others decelerated. This results in a longitudinal density modulation of the electron beam at the optical wavelength during the passage through the undulator. With the onset of this "micro-bunching", coherent emission at the resonant wavelength sets in which results in an exponential growth of the power in the radiation field (high gain mode), characterized by the gain length L_{gain} :

$$I(z) = I_0 \cdot \exp(z / L_{gain})$$

Similar to synchrotron radiation sources, there is no fundamental limit in the choice of the photon wavelength.

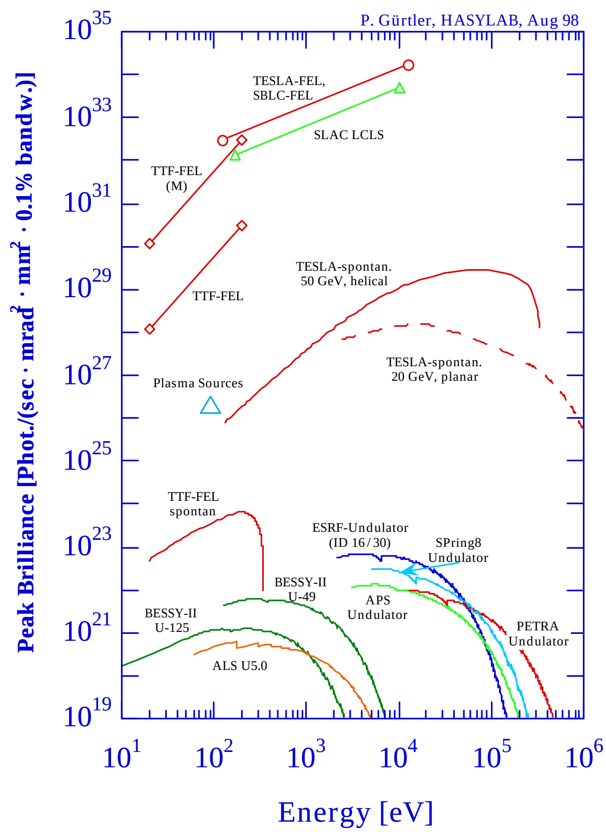

Fig. 1. Spectral peak brilliance of short-wavelength FELs compared with third generation radiation sources and plasma lasers. For comparison, the spontaneous spectrum of an X-ray FEL undulator at 20 GeV is also shown.

The photon wavelength λ_{ph} of the first harmonic is related to the period length of a planar undulator λ_u by

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad , \qquad (1)$$

where $\gamma = E/mc^2$ is the relativistic factor of the electrons and $K = eB_u\lambda_u/2\pi mc$ the 'undulator parameter', e being the elementary charge, m the electron rest mass, c the speed of light, and B_u the peak field in the undulator. It is seen that very short photon wavelength can be achieved if only the electron energy (i.e. γ) is chosen sufficiently high.

For most FELs presently in operation, the electron beam quality and the undulator length result in a gain of only a few percent per undulator passage, so that an optical cavity resonator and a synchronized multi-bunch electron beam have to be used. For the TESLA FEL however, we aim at very short wavelength, for which normal-incidence mirrors of high reflectivity are not available. Thus we have to provide an electron beam quality (emittance, peak current, energy spread) good enough and an undulator long enough to reach the power saturation level within a single passage. At the saturation length $L_{sat} \approx 4\pi L_{gain}$, the electrons run out of resonance due to their energy loss.

Since the desired wavelength is very short, there is no conventional laser to provide the “initially existing radiation field”. Instead, one may consider the spontaneous undulator radiation from the first part of the undulator as an input signal to the downstream part of it. FELs based on this principle of Self-Amplified-Spontaneous-Emission (=SASE) [2,3] are presently considered the most attractive candidates to deliver extremely brilliant, coherent light with wavelength in the Angstrom regime[4-6]. Compared to state-of-the-art synchrotron radiation sources, one expects full transverse coherence, larger average brilliance, and, in particular, up to eight or more orders of magnitude larger peak brilliance (see Fig. 1) at a pulse lengths of about 200 fs FWHM. An important step has been done recently in demonstrating a SASE FEL gain larger than 10^5 at 12 μm wavelength [7].

2 SASE FEL RADIATION

Theoretical description of SASE distinguishes three steps of the process: The start-up-from-noise (or lethargy) regime, the steady-state regime and the saturation regime. The steady-state regime, where a well-defined external electromagnetic input wave is linearly amplified resulting in exponential growth, is accessible for analytical and numerical treatment since many years. The start-up from noise process, however, is much more difficult to analyze, since it is determined by statistical properties and by mutual interaction of more than 10^9 radiating particles. Fully 3-dimensional simulations became available only recently. One of these codes uses Cartesian coordinates and performs direct solution of the paraxial equations for the radiation field and is thus capable of dealing with arbitrary undulator field errors [22]. The other one [23] uses a Greens-function approach for calculation of the radiation field, is much faster and includes far-field mode analysis of the radiation. Results of these codes are in perfect agreement with a SASE proof-of-principle experiment performed recently in Los Alamos at 12 μm wavelength [7, 23]. Finally it is noted, that fluctuation properties of SASE FEL radiation have been analyzed both in the linear and in the saturation regime [24]. Experimental results obtained for the linear regime are again in agreement with theory and simulation, while experimental results on saturation are not yet available.

3 THE TESLA FEL CONCEPT

TESLA aims at a 500 GeV e+/e- collider with integrated X-ray laser Facility [6]. The TESLA linac is indeed exceptionally well suited for a short-wavelength Free Electron Laser: Excellent beam quality is maintained during acceleration and a large variety of pulse train patterns can be provided to users.

The problem with SASE FELs is that, in going to shorter and shorter wavelengths, several technical problems arise such as:

- Some 100m long undulators
- Small (normalized) emittance around 1 π mrad mm for a 1 nC bunch charge
- Bunch compression down to 25 μm bunch length

The ambitious goal of an 1 Å FEL is approached in three steps. Table 1 summarizes main parameters of both electron and photon beams for all these steps.

1. **TTF FEL Phase 1** (approved) [8]: A SASE FEL experiment at wavelength down to 42 nm using the 390 MeV TESLA Test Facility (TTF) linac at DESY[9], see Fig. 2. Besides proving the principle, technical components will be tested: the rf photoinjector, bunch compressors, a 14m long undulator, diagnostics for both electron and photon beams. First operation is scheduled for 1999.

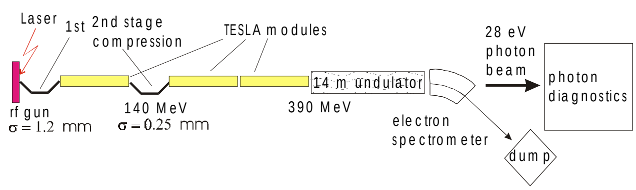

Fig. 2: Schematic layout of phase 1 of the SASE FEL project based on the TESLA Test Facility at DESY.

2. **TTF FEL Phase 2** (approved) [10,11]: By adding 5 more TESLA modules [12], the linac will be upgraded to (at least) 1 GeV, bringing the wave-length down to 6 nm, see Fig. 3. The undulator will be 27m long and the rms bunch length will be reduced to 50 μm by a further compressor stage. Open to users by the year 2003, this facility will give the opportunity to develop experimenting techniques with extraordinary photon beam characteristics like high peak power, short pulse length and fluctuating, spiky substructure typical for SASE FEL photon pulses [13].
3. **TESLA** linear collider with Integrated X-ray Laser (in its technical design phase) [5,6]. For large field gradients, even a superconducting linac has to operate in a pulsed mode. Thus there is room for adding further rf pulses between those driving the high-energy physics beam. By adding a specialized injector providing the electron beam properties needed for the FEL, one can utilize a linear collider installation for driving an X-ray FEL without mutual interference. The plan is to eject the electron bunch train for the FEL at the required beam energy (e.g. at 50 GeV) in the TESLA tunnel, and then transport it to the TESLA interaction region, where a big enough area could accommodate both the high energy physics experimental halls and the X-ray laboratory. A schematic of a switchyard distributing the bunch train over different radiation facilities is shown in Fig. 4.

Concerning the necessary electron beam parameters, all the critical issues are being addressed during phases 1 and 2 (see also Table 1): An rf photoinjector with small emittance and many thousand bunches within each rf pulse [14], bunch length compression by magnetic chicanes including control of coherent radiation effects [15], acceleration without beam degradation [16], and long undulators combined with a periodic FODO lattice [17,18]. In the remainder of this paper we briefly address some key issues of these components.

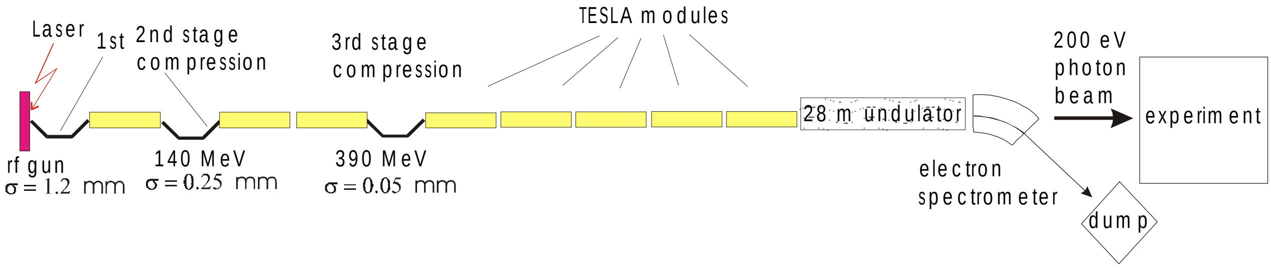

Fig. 3. Schematic layout of phase 2 of the SASE FEL project based on the TESLA Test Facility at DESY. The linac consists of 8 TESLA modules, each 12.2m long. The over-all length of phase 2 is some 300 meters.

Parameter	**Units**	**TTF FEL Phase 1**	**TTF FEL Phase 2**	**TESLA X-ray FEL***
beam energy	GeV	0.300	1.000	25.0
λ_{ph} (radiation wavelength)	nm	71	6.4 (193 eV)	0.1
λ_u(undulator period)	mm	27.3	27.3	50
Effective undulator length	m	13.5	27	87
rms beam size	µm	70	50	18
ε^n (normalized emittance) in the undulator	π mrad mm	2.0	2.0	1.0
peak electron current	A	500	2490	5000
No. of electrons per bunch		6.24E+9	6.24E+9	6.24E+9
No. of photons per bunch		1.7E+14	4E+13	7E+12
rms energy spread σ_γ/γ	10^{-3}	1.7	1.00	0.04 at entrance
rms bunch length σ_S	µm	250.	50.	25
L_g (power gain length)	m	0.6	1.00	4.1
P_{sat} (saturated peak power)	GW	0.3	2.6	65
Average brilliance [photons/s/mm^2/mr/0.1%]		up to 2E+21	up to 6E+22	8E+25
bunch train length	µsec	800	800	1052
Number of bunches per train		Up to 7200	up to 7200	Up to 11315
Repetition rate	Hz	10	10	5

Table 1: Main parameters of the TESLA Test Facility FEL (TTF FEL), phases 1 and 2 [10] and of the TESLA X-ray FEL[6]. The insertion devices are planar hybrid undulators. These values should be used as a guideline only since experimental experience has still to be gained in this wavelength regime.

*) For the TESLA X-ray FEL there will be a beam switchyard serving a number of FELs operating at different wavelengths down to 1 Angstrom, and using different beam energies. The parameters given are typical for the 1 Angstrom case.

4 THE PHOTOINJECTOR

The electron source consists of a 1½ cell , 1.3 GHz normal conducting resonator and a photocathode located at the mid-plane of the first (1/2) cell, where the accelerating field is maximum (approx. 45 MV/m). The klystron must provide 4.5 MW power at up to 800 µs pulse length for the long bunch train that can be accelerated in the s.c. linac,. Thus, since the gun cavity is normal conducting, thermal load is a critical issue. The mechanical design provides direct water cooling of the irises and avoids any brazing between water channels and vacuum. For achieving minimum emittance in all 3 dimensions, the design criteria are

- High accelerating gradient to reduce transverse space charge effects.
- Coaxial rf input coupling to reduce rf asymmetries in the cavity.
- Optimum position of the solenoid focussing field to achieve, in the subsequent drift space, “space charge compensation” [19].
- Short laser pulses.

5 THE BUNCH COMPRESSOR

In phase 1, two stages of longitudinal bunch compression are foreseen to reach the high peak current (500A) that is needed to achieve high FEL gain. This compression is done at beam energies high enough so that space charge forces are tolerable. The key compression step is at 140 MeV from 1 mm to 0.25 mm rms bunch length and consists of a 4 dipole magnet chicane. While magnet chicane compression, using path length differences of particles with different momenta, is the only possible way for ultra-relativistic particles, this method unavoidably involves radiation effects when electrons pass the dipole magnets. It has been shown [17,20] that space charge forces and coherent radiation need to be treated simultaneously in order to describe properly beam dynamics. Radiation effects are the dominant contribution to emittance growth in our chicane, see Fig. 5.

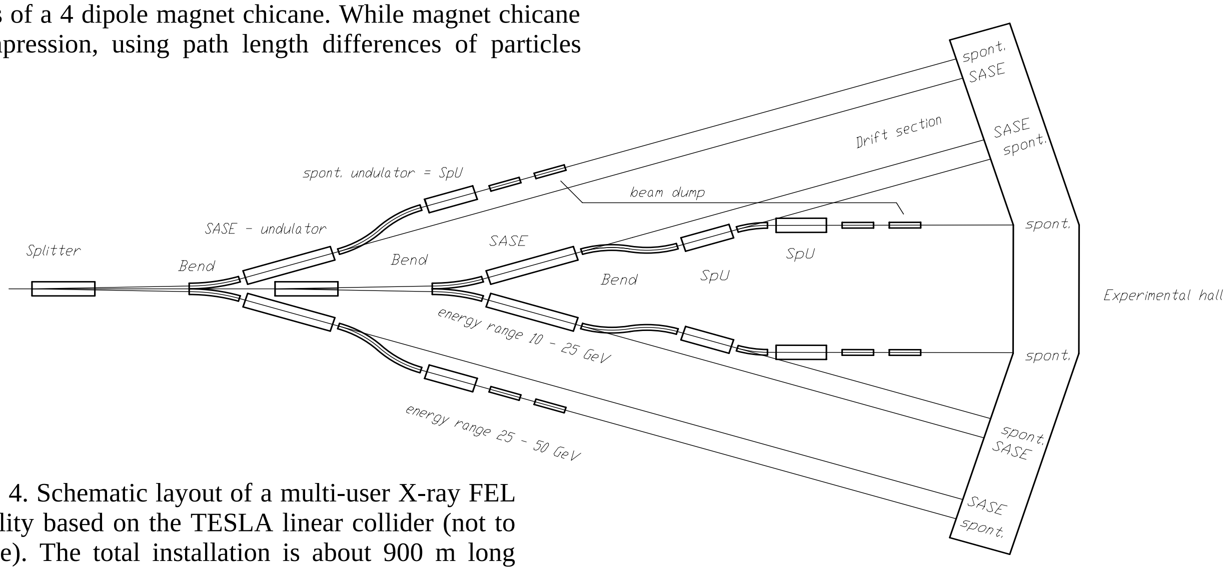

Fig. 4. Schematic layout of a multi-user X-ray FEL facility based on the TESLA linear collider (not to scale). The total installation is about 900 m long and 200 m wide and would be located on the same site as the linear collider interaction region.

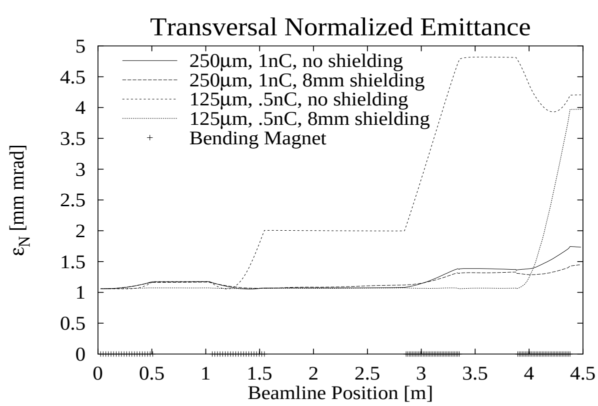

Fig. 5: Evolution of the uncorrelated emittance at the longitudinal center of the electron bunch passing bunch compressor 2. Coherent radiation and space charge are taken into account in this simulation [17]. Two different parameter set are considered, corresponding both to 500 A peak current in the bunch. It is seen that the 125 µm case is more heavily affected.

Significant suppression of coherent radiation by the metallic vacuum chamber is expected at a vacuum chamber height below 8 mm. For experimental verification of this theoretical prediction, the chamber height of bunch compressor 2 will be varied during phase 1 operation. Another issue of test operation will be the stability of rf phase vs. laser phase, since this determines stability of the bunch length, particularly in view of compressor 3. Phase stability below 1 ps has been demonstrated for both the laser and the klystron, which should be sufficient to reach 50 µm rms bunch length in phase 2.

Although compression takes place at high beam energies, space charge turns out to be critical for the whole TTF FEL beam line, from the gun to the undulator, and needs to be taken into account even in the linear optics calculation.

6 BEAM DYNAMICS IN THE ACCELERATOR

Besides space charge and coherent radiation, also wakefields may degrade beam quality. In spite of the low rf frequency of TESLA, longitudinal wake fields are still a concern due to the extremely small bunch length (or to be more precise, due to the large time derivative of the bunch current). It has been shown in [16] that the wake potential of a short bunch is considerably modified while the bunch is passing a longer and longer accelerator structure. For the TTF, the asymptotic case of an infinitely long, periodic structure is reached well before the end of the linac. The bunch still generates extremely high frequency components >680 GHz for which Niobium is known to loose superconductivity. Absorption of these frequency components in the Niobium walls does not seem to be a problem regarding superconductivity, nevertheless, but it may increase the dynamical cryogenic load on the 2K Helium level [21]. Experimental studies on this issue is a subject of TTF FEL, as well as the optimum technical realization of higher order mode absorbers and additional wake fields due to surface roughness of the vacuum pipe.

7 LONG UNDULATORS

The main technological challenge of the FEL undulator is that the electron beam trajectory must be straight within a tolerance of 10 µm over several meters. This is particularly difficult to achieve since strong quadrupole focussing is superimposed to the undulator field in order to realize the small β function of about 1 m which is optimum for maximum FEL gain. The undulator for TTF FEL phases 1 and 2 is made in permanent magnet, hybrid technology with modules 4.5 m long each [17], see Fig. 6. Since it is impossible to guarantee this straightness from undulator field measurement alone, a beam based alignment strategy has been worked out using a large number of high-resolution beam position monitors [18].

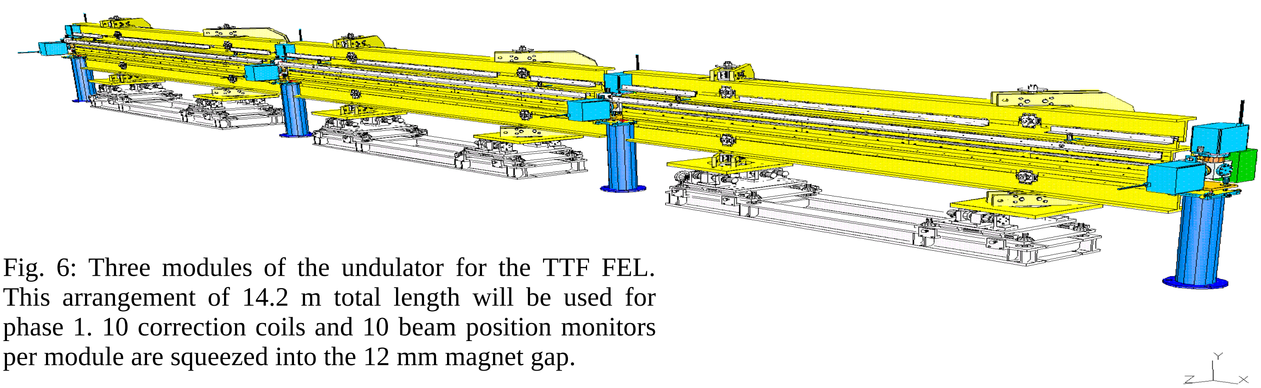

Fig. 6: Three modules of the undulator for the TTF FEL. This arrangement of 14.2 m total length will be used for phase 1. 10 correction coils and 10 beam position monitors per module are squeezed into the 12 mm magnet gap.

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