Studies on a Free Electron Laser for the TESLA Test Facility

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Abstract

We present the layout of a Single Pass FEL to be driven by the TESLA Test Facility (TTF) currently under construction at DESY. The TTF is a test-bed for high-gradient, high efficiency superconducting accelerating sections for a future linear collider. Due to its unrivaled ability to sustain high beam quality during acceleration, a superconducting rf linac is considered the optimum choice to drive a Free Electron Laser (FEL). We aim at a photon wavelength of $\lambda = 6$ nm utilizing the TTF after it has been extended to 1 GeV beam energy. A first test is foreseen at a larger photon wavelength.

1. GENERAL DESCRIPTION

A Free Electron Laser (FEL) in the soft X-ray regime is under study, using the superconducting linac of the TESLA Test Facility (TTF) being under construction at DESY [1]. The FEL at the TESLA Test Facility (TTF FEL) is based on the principle of 'Self Amplified Spontaneous Emission' (SASE) [2]. The key advantage of the SASE scheme compared to other FEL schemes is that neither an input seed laser is required nor mirrors forming an optical cavity. Thus, no known fundamental limitation would prevent operation even down to the Ångstrom region. In the first section of the undulator the electrons radiate independently and the phases of the photons are randomly distributed. Since microbunch formation starts from this „random“ noise, a long undulator is needed to achieve laser action with exponential growth in light output. For the TTF FEL an overall undulator length of 30 m is planned.

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

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

where, $\gamma = E/mc^2$ is the relativistic factor of the electrons and $K = e\, B_u\, \lambda_u / 2\pi mc$ 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.

The physics program for the TTF FEL requires a photon wavelength of 6 nm. Therefore, for state-of-the-art undulator parameters are assumed, e.g. $\lambda_u = 27$ mm, $K = 1.3$, a beam energy of 1GeV is necessary.

Two beam parameters are essential to reach power saturation within a not too long undulator: A small transverse beam emittance ε_t to provide both small beam diameter and small beam divergence in the undulator, and a small longitudinal beam emittance ε_z to achieve kilo-Ampere instantaneous beam currents at an energy width in the 0.1% range.

The TTF is an ideal accelerator to drive a SASE FEL. There are two main reasons:

- The perturbation of small emittance beams during the acceleration process is smallest with a superconducting linac at lower frequency. Because the resonator volume and the stored energy are big, the accelerating field is hardly affected by the presence of the electron beam. The variation of the effective accelerating voltage over the bunch length („longitudinal wakefield“) is minimum and the tendency of beam induced rf deflections („transverse wakefields“) is small.
- A superconducting linac provides a large AC power efficiency and a high duty cycle. The TESLA Test Facility will operate at 1 % duty cycle, orders of magnitude larger than a normal conducting linac would do at the TTF nominal gradient of 15 MV/m. In addition to power efficiency, this is another crucial advantage for potential experiments, because it leaves sufficient time between pulses in the bunch train for data handling.

The most expensive single component of a short wavelength FEL is the accelerator. Taking into account,

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that a SASE FEL needs beam parameters similar to those to be realized for a Linear Collider, it is obvious that the TTF linac can be ideally utilized for driving a SASE FEL. For the discussion of the TESLA Test Facility linac and its relation to the TESLA 500 Linear Collider scheme we refer to the TTF Design Report [1].

The TTF design energy is 500 MeV. It has to be upgraded to 1 GeV electron beam energy required for the desired photon wavelength. Figure 1 shows the overall TTF FEL scheme. Table 1 compiles main parameters of the TTF FEL.

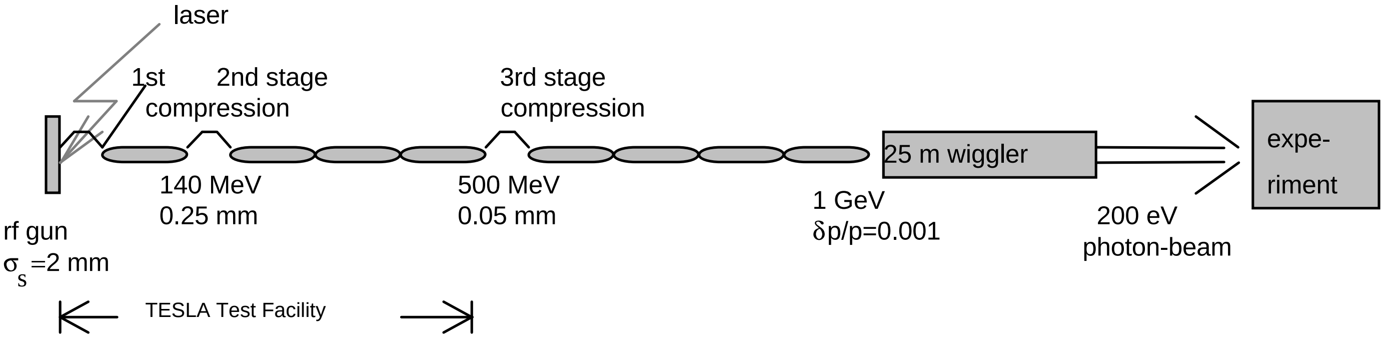

Figure 1: Schematic layout of the TTF FEL based on the TESLA Test Facility (TTF). Four additional TESLA accelerator modules bring the energy up to 1 GeV. The bunch length is reduced from 2 mm to 50 µm within three steps of bunch compression. The SASE FEL process requires an undulator of 25 m effective length. The over-all length of the facility is some 200 meters.

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2. ELECTRON SOURCE

The transverse coherence condition imposes a tight requirement on the transverse emittance ε_t of the electron beam [3]:

$$\varepsilon_t^n \leq \frac{\gamma \cdot \lambda_{ph}}{4\pi}$$

ε_t^n is the *normalized* emittance. For λ_{ph} = 6 nm, γ = 2000, this requires $\varepsilon_t^n < 1\ \pi$ mrad mm. Actually, as is seen from Figure 2, this condition is not very strict, but the saturation length significantly increases if ε_t^n is larger. Thus, we aim at $\varepsilon_t^n = 1\ \pi$ mrad mm for the rms electron emittance of a 1 nC bunch charge from the electron gun, and we allow for a factor of two emittance dilution during longitudinal beam compression and acceleration up to 1 GeV. According to beam dynamics simulations in both the bunch compressors and the accelerator, this seems to be a conservative assumption. These very high phase space densities came into reach due to two major achievements: The development of the rf gun [4] and the concept of space charge compensation [5].

3. UNDULATOR

The undulator is the most prominent FEL specific component. The proposed design avoids technical risks. A planar hybrid undulator is foreseen with period length λ_u = 27 mm and peak magnetic field B_u = 0.5 T, parameters very much like those of existing undulator magnets. The main challenges are the total length of 30 m, the additional quadrupole focusing to be supplied and tight tolerances. To simplify production, measurement and installation, 5m long modules are forseen. This also permits installation of electron and photon beam monitors and correction elements.

VARIABLE	**UNITS**	**VALUE**
beam energy	GeV	1.000
λ(radiation wavelength)	nm	6.4 (193 eV)
λ_u (undulator period)	mm	27.3
undulator gap	mm	12
B (undulator peak field)	T	0.497
undulator length	m	25
beam optics β function	m	3
rms beam size	mm	0.05
ε^n (normalized emittance) in the undulator	π mrad mm	2.0
peak electron current	A	2490
number of electrons per Gaussian bunch		6.24E+9
number of photons per Gaussian bunch		4E+13
peak electron beam power	GW	2490
energy spread σ_γ/γ	10^{-3}	1.00
bunch length	µm	50.
L_g (power gain length)	m	1.00
L_S (saturation length)	m	< 25
P_{sat} (saturated power)	GW	3
average brilliance [photons/s/mm^2/mr/0.1%]		up to 6E+21
bunch train length	µsec	800
number of bunches per train		up to 7200
repetition rate	Hz	10

Table 1: Main parameters of the TESLA Test Facility FEL (TTF FEL). The insertion device is assumed to be a planar hybrid undulator. These values should be used as a guideline only since the optimization has not yet been finished and experimental experience has to be gained in this wavelength regime.

4. FEL PROCESS

Various computer codes have been used to investigate the start-up from noise, and the lethargy, exponential and saturation regimes, respectively, e.g. NUTMEG [6], GINGER[7], FS2R[8], TDA[9,10]. There is no essential disagreement between results of all these codes written by different groups and based on different approaches. It should be noted though, that for a complete study of the shot noise startup the time dependence of the input noise and the slippage effects should be taken into account in the theory and in the simulations. The one-dimensional analysis shows that a critical parameter for shot noise analysis is the beam length in units of the "cooperation length" [11]:

$$\lambda_c = \frac{\lambda}{4\pi\rho}\,.$$

For the TTF FEL the cooperation length is 0.26 μm, and the beam length is 50 μm. In this case bunch-to-bunch fluctuations should be a fraction of a gain length and the use of an equivalent input signal analysis should be adequate. A more careful study with existing time dependent FEL codes (GINGER and FELEX) is in its starting phase and will be reported soon. Figure 2 shows the emitted intensity as a function of ε^n.

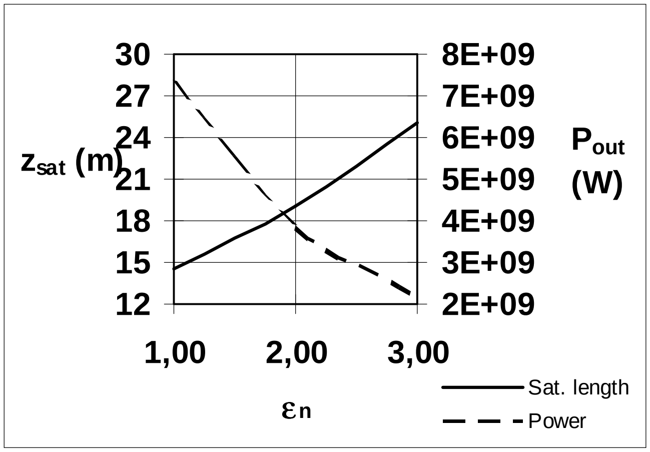

Figure2: Emitted intensity and saturation length at the peak gain as a function of the normalized electron beam emittance, for the nominal energy spread of 0.1%.

In order to determine the performance of the FEL including the undulator field errors, first simulations have been performed with the simulation code TDA3D [10]. The goal is to systematically study the correlation between phase shake and FEL parameters like saturation length and peak power. These simulations will include the undulator plus the superimposed quadrupole focusing. Figure 3 shows the photon flux emitted by the TTF FEL.

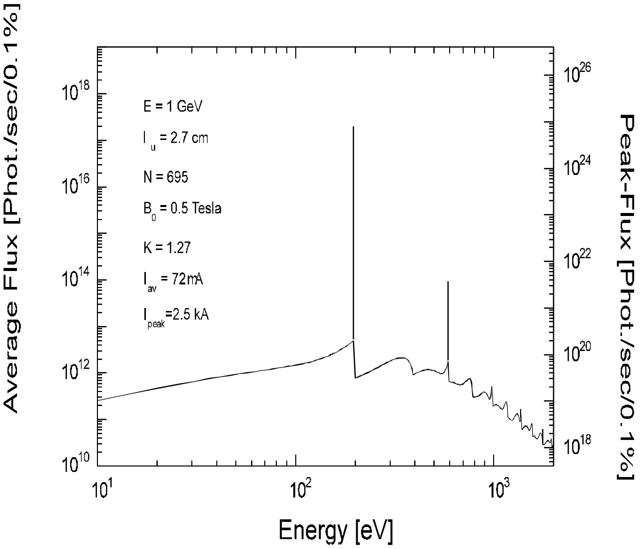

Figure 3: Expected photon flux emitted by the TTF SASE FEL. The two peaks correspond to the FEL emission at the fundamental and 3rd harmonic. The lower curve is the spontaneous emission in the undulator.

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