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A VUV FREE ELECTRON LASER AT THE TESLA TEST FACILITY AT DESY

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Abstract

We present the layout of a Single Pass Free Electron Laser (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 acceleration 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 FEL. We aim at a photon wavelength of $\lambda = 6$ nanometers utilizing the TTF after it has been extended to 1 GeV beam energy. Due to lack of mirrors and seed-lasers in this wavelength regime, a single pass FEL and Self-Amplified-Spontaneous-Emission (SASE) is considered. A first test is foreseen at a larger photon wavelength. The overall design as well as both electron and photon beam properties are discussed.

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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 [1,2]. The FEL at the TESLA Test Facility (TTF FEL) is based on the principle of 'Self Amplified Spontaneous Emission' (SASE) [3,4]. Since in the SASE scheme microbunch formation starts from noise, a long undulator is needed to achieve laser action with exponential growth in light output [5]. For the TTF FEL an overall undulator length of 30 m is planned.

Figure 1 shows the overall TTF FEL scheme. Table I compiles main parameters of the TTF FEL. Figure 2 illustrates the spectral brilliance of the TTF FEL in comparison with second and third generation synchrotron radiation sources and the LCLS Free Electron Laser project discussed at SLAC, Stanford, USA [6].

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

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

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.

Considerable effort has been made to define an FEL parameter set that is attractive to a wide community of potential users[7]. The physics program for the TTF FEL covers applications ranging from magnetic materials research and various pump-and-probe experiments to photochemistry and X-ray microscopy of biological samples. This program requires a photon wavelength below about 6 nm. Therefore, if state-of-the-art undulator parameters are assumed, e.g. $\lambda_u = 27$ mm, $K = 1.3$, a beam energy of 1 GeV 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_s to achieve kilo-Ampere instantaneous beam currents at an energy width in the 0.1% range.

The superconducting linear accelerator currently under construction at DESY 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. It is useful to understand that a SASE FEL needs beam parameters similar to those to be realized for a Linear Collider. Thus, the TTF linac can be ideally utilized for driving a

SASE FEL, and there is an extensive common interest in R&D on beam handling and diagnostics. 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]. It is noted that the TTF FEL is considered a necessary step to pave the way towards an Ångström FEL which is part of the TESLA500 linear collider scenario.

The TTF design energy is 500 MeV. It has to be upgraded to 1 GeV electron beam energy required for the desired photon wavelength.

2. ELECTRON SOURCE

The transverse coherence condition imposes a tight requirement on the transverse emittance ϵ_t of the electron beam [8]:

$$\epsilon_t^n \leq \frac{\gamma \cdot \lambda_{ph}}{4\pi} \quad (2)$$

ϵ_t^n is the normalized emittance. For $\lambda_{ph} = 6$ nm, $\gamma = 2000$, Eq. (2) requires² $\epsilon_t^n < 1 \pi$ mrad mm. Actually, as is seen from Figure 4, this condition is not very strict, but the saturation length significantly increases if ϵ_t^n is larger. Thus, we aim at $\epsilon_t^n = 1 \pi$ mrad mm for the rms electron emittance of a 1 nC bunch charge from an rf electron gun [9], 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.

In spite of very quick acceleration (typically about 30 MV/m in an L-band gun), there is still considerable emittance growth due to space charge forces. By applying solenoid focusing, a bunch rotation in phase space can be performed such, that there is mutual compensation of space charge effects before and after this focusing [10]. First investigations show that, using the described technique, the required emittance should be feasible [11,12,13].

3. LONGITUDINAL BUNCH COMPRESSION AND BEAM DYNAMICS

As mentioned before, a very high instantaneous beam current is needed in the undulator to reach photon power saturation within a reasonable undulator length. For the TTF FEL, this number is 2500 A, corresponding to 50 μ m rms bunch length for a 1 nC bunch charge. This value is not attainable directly from the electron gun, because space charge forces would blow up both the transverse beam size and the momentum spread. Thus, the use of magnetic bunch compression is foreseen in order to reduce the rms bunch length from 2 mm in three steps down to 50 μ m.

In principle one could consider performing the bunch compression in one step at an energy level, where space charge is not critical any more (> 300 MeV or so). However, even at the comparatively low TTF rf frequency, the cosine-like time dependence of the accelerating field would then impose an intolerable nonlinear correlated energy distribution along the bunch. The proposed solution is to perform compression in three

² The factor π is only included in the dimensions to indicate that the numerical value of the emittance (in the present case 1) does *not* include π . Following common practice, we nevertheless omit the factor π in formulae describing the beam size etc., i.e. we write $\sigma = \sqrt{\epsilon_t \beta}$, instead of, in a mathematically rigorous way, $\sigma = \sqrt{\epsilon_t / \pi \cdot \beta}$

steps at 22 MeV (2 mm $\rightarrow$ 0.8 mm), 140 MeV (0.8 mm $\rightarrow$ 0.25 mm) and 500 MeV (0.25 mm $\rightarrow$ 0.05 mm) [14].

The uncorrelated energy spread of the beam leaving the gun is around 25 keV, its length 2 mm. The SASE process requires less than 1000 keV energy spread at the undulator. Thus, the initial longitudinal emittance of around 50 mm·keV is already close to the finally tolerable emittance, and the emittance blow up during compression has to be kept small. The final bunch length is basically determined by the ratio of initial to induced energy spread.

Since neither space charge effects nor the nonlinearity of the accelerating voltage nor longitudinal wakefields are completely negligible, computer simulation is required to get a realistic model of beam behaviour along the linac. First results of such an analysis indicate that the aforementioned sequence of compressions seems to be adequate. Figure 3 illustrates an output of such an analysis. It is noted that, due to the comparatively small wakefields in the TESLA modules, the bunch compression scheme does not rely on an exact knowledge of the shape and magnitude of longitudinal wakefields.

4. UNDULATOR

The undulator is the most prominent FEL specific component. It has two functions:

1. It has to provide the sinusoidal field so that the FEL process can take place.
2. In order to keep the beams size small over the whole undulator length, the undulator has to be supplied with an alternating field gradient provided by a superimposed quadrupole lattice.

The proposed design [15] minimizes technical risks. A planar hybrid undulator is foreseen with period length $\lambda_u = 27$ 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. First computer simulations with TDA3D on undulator errors indicate that the most critical parameter is the misalignment between electron beam and photon beam (required to be smaller than some 10 μ m), while phase fluctuations of the radiation field would become critical only at much larger peak field fluctuations [16].

To simplify production, measurement and installation, 5m long undulator modules are foreseen. This also permits installation of electron and photon beam monitors and correction elements inbetween.

5. 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 [17], GINGER [18], FS2R [19], TDA3D [20,21]. There is no essential disagreement between results of all these codes written by different groups and based on different approaches [22]. A critical issue for a SASE FEL is to take into account the time dependence of the input noise and the slippage effects 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" [23]:

$$\ell_c = \frac{\lambda}{4\pi\rho}.$$

For the TTF FEL the cooperation length is $0.26\text{ }\mu\text{m}$, and the beam length is $50\text{ }\mu\text{m}$. 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. This is in agreement with 2D GINGER simulations [24].

A peculiar characteristic of the SASE FEL is the strong spiking both in the temporal and spectral domain of the emitted radiation. It is a consequence of longitudinal subsections inside each electron bunch radiating at statistically independent phases if the start-up is from noise instead of being „seeded“ by an external radiation field of high longitudinal coherence (i.e. by a „seed laser“). Calculations with GINGER have confirmed the presence of strong spikes, with a duration of the order of a cooperation length and peak power of about 10 GW [24].

After saturation the FEL behavior is determined by the nonlinear regime of the spikes. The total linewidth (half width half maximum) has been estimated using GINGER at 0.1% [24], which is, due to diffraction effects, even smaller than the FEL parameter, $\rho=0.2\%$, which is the expected value from the 1D time dependent model.

As seeding at 6 nm is impossible due to lack of lasers, schemes generating harmonic content of the longitudinal electron density modulation at (roughly) the 40th harmonic of a conventional laser could be considered (multiple stage harmonic generation [25]). Further studies on these schemes are desirable, but they are presently not proposed for the TTF FEL, because the TTF FEL aims at establishing the SASE mechanism for short wavelengths in order to prepare for an Ångström FEL, on which the multiple stage harmonic generation scheme is even more unlikely to be applicable.

Since, in view of the present state of the art, to achieve the desired transverse electron beam emittance seems to be possible but by far not trivial, the dependence of radiation properties on beam emittance has been studied. Figure 4 shows the emitted intensity as a function of ϵ_t^n .

Figure 5 shows the photon flux emitted by the TTF FEL without field errors taken into account.

TTF FEL PHASE 1

In order to learn as quick as possible, it is foreseen to perform a first SASE FEL test just after the TESLA Test Facility has been commissioned. This will be in the electron beam energy range between 300 and 500 MeV. Using two or three of the final undulator modules, the resonant photon wavelength will be much larger. Therefore, beam requirements can be relaxed: larger transverse emittance and longer bunch length will be tolerable. The main objectives of this phase are observation of startup from noise and exponential regime, commissioning of all but the final bunch compressors and beam diagnostics. No operation for users is planned during this phase 1 operation.

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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 GeV. The bunch length is reduced from 2 mm to 50 mm 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.

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
effective undulator length (excluding drift spaces between modules)	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
rms energy spread σ_γ/γ	10^{-3}	1.00
rms bunch length σ_s	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 I: 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.

Figure 2: Spectral brilliance of the TTF FEL in comparison with second and third generation synchrotron radiation sources and the LCLS Free Electron Laser project discussed at SLAC, Stanford, USA[5]. The open triangles represent values achieved with plasma lasers under the optimistic assumption that they can fire once a second.

Figure 3: Longitudinal phase space (GeV-m)

Figure 4: 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%.

Figure 5: 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.