The TESLA Free Electron Laser

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Abstract

The TESLA Free Electron Laser [1] is an ultra-brilliant X-regime light source (XFEL). It adopts the lasing principle of self-amplified spontaneous emission (SASE). To demonstrate the feasibility of the SASE principle at short wavelength, DESY is now pushing, in the frame of international collaboration, to constructing an FEL test facility (TTF FEL) in parallel with the TESLA Test Facility (TTF) for the high energy physics. The TTF FEL is driven by a 390 MeV beam, lasing at 42 nm. An upgrading to a 1 GeV beam at 6 nm is foreseen.

The low RF frequency of 1.3 GHz for TESLA is ideal to drive such kind of SASE beam, which requires a normalized transverse emittance of 1 π mm-mrad at 1 nC per bunch with an rms bunch length of only 25 μm. Moreover, the superconducting accelerating structure used by TESLA favors a multibunch operation. With the large cavity volume, the beam loading should be reduced to its minimum, which is again beneficial to the stringent requirement on the uncorrelated energy spread of 0.1%.

Simulation results of various components of the FEL show that the FEL design goal is quite challenging but feasible. The gun is optimized to produce a high quality beam of normalized transverse emittance $\epsilon^n_{x,y} = 0.9\pi$ mm-mrad, longitudinal emittance $\epsilon_s = 27$ mm-keV, and rms bunch length $\sigma_s = 1$ mm. It is shown that the critical coherent synchrotron radiation (CSR) in a chicane bunch compressor can be properly handled to maintain a growth in energy spread within 0.04%. TESLA cavity of nominal accelerating gradient of 15 MV/m will be used. This gradient is already more than three times higher than the highest currently routinely used. An even higher gradient of 25 MV/m is quite within reach. For the radiator, we will use a planar combined function undulator of permanent magnets (PM). Lateral beam wandering along the undulator should be kept within 10 μm.

All the components necessary for the TTF FEL proof-of-principle operation are well under construction. First beam operation is scheduled spring 1999. This paper will give a brief description of the above components with respect to their theoretical and practical aspects.

1 INTRODUCTION

Since mid 60's, synchrotron radiation (SR) has opened a new research field of its own like diffraction analysis, nuclear resonant scattering, spectroscopy, imaging, etc.. Radiation wavelength, brilliance, and pulse width are three major parameters to characterize a photon radiation.

The shorter the wavelength, the sharper one could "see". With little exaggeration, the entire human-being's written theories of almost all kinds are obtained directly and indirectly through our eyes. Unfortunately, current SR sources are still too "dim" at Å wavelength regime, though the spectrum is quite broad. To study instant or dynamic processes, time-resolved flashes are indispensable, sometimes even down to femtosecond (fs) level. The best solution to all these conflicts would be the traveling-wave-tube (TWT)-like single pass free electron laser. This scheme uses the fact that electron bunches can be sub-bunched by the electromagnetic waves which are emitted by themselves due to curved paths. A small fraction of the radiation spectrum is, if in phase, in turn, amplified by the sub-bunched electrons. Treating the initial spontaneous radiation with uncorrelated phases as an input signal, this laser scheme is something like a microwave traveling-wave-tube in their very principle. The helical slow-wave winding in a TWT has the same bunching effect as the wiggling of the electron beam in an FEL. This lasing scheme is referred to as self-amplified spontaneous emission (SASE) [2] [3].

The basic principle on FEL was given by J.M.J. Madey in 1971 [4]. Before applying the SASE principle to X-regime, we should make a proof-of-principle test at nm or optical wavelength range. DESY is now, in the frame of international collaboration, pushing in this direction, building an FEL test facility in the VUV wavelength regime [5]. The ultimate goal of the TESLA FEL is to reach an Å-regime multi-GW high brilliance SASE laser, the XFEL by name [6]. It should deliver an X-ray at an unprecedentedly high brilliance of at least 8 orders of magnitude (peak) and 5 orders of magnitude (average) higher than that ever achieved with the SR sources (Figs. 1 and 2).

The phase I of the TTF FEL project, which has been approved, is to reach a 42 nm lasing with a 390 MeV beam through a 13.5 meter-long undulator. In phase II, we will extend the beam energy to 1 GeV, reaching 6 nm using a 27 meter undulator. An undulator of 100 meters long is foreseen for the XFEL at 1 Å.

2 THE BASICS AND BOUNDARY CONDITIONS

As known, necessary beam emittance ϵ scales linearly with the laser wavelength in the following way [7]:

$$\epsilon \leq \frac{\lambda_\gamma}{4\pi}. \tag{1}$$

For $\lambda_\gamma = 6$ nm and $\gamma = 2000$ (i.e. 1 GeV beam), one obtains a normalized emittance of 1π mm-mrad. To ensure a high lasing gain, peak current should be in a range of kA or even higher. Due to strong space charge repulsion near the

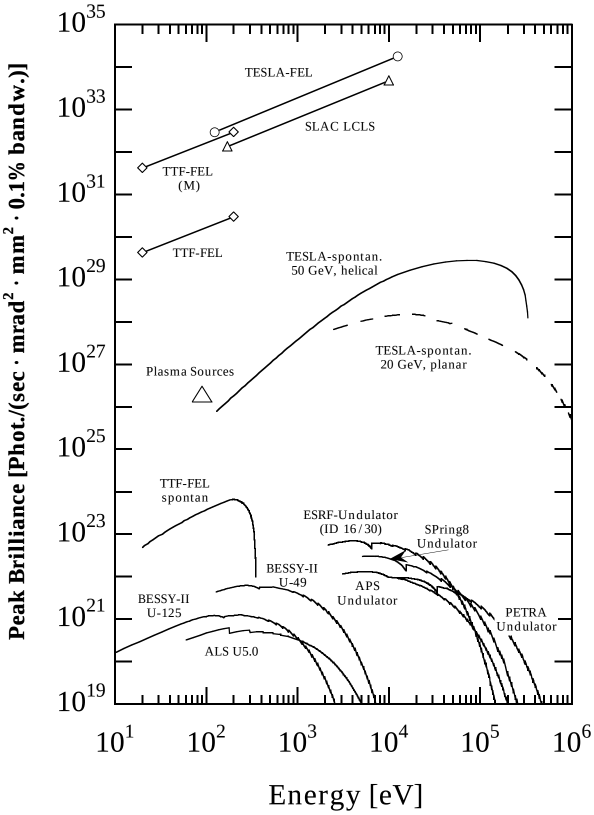

Figure 1: Spectral peak brilliance of XFELs based on the TESLA linear collider, together with that of third generation synchrotron radiation sources and the LCLS project discussed at SLAC, Stanford, USA [8]

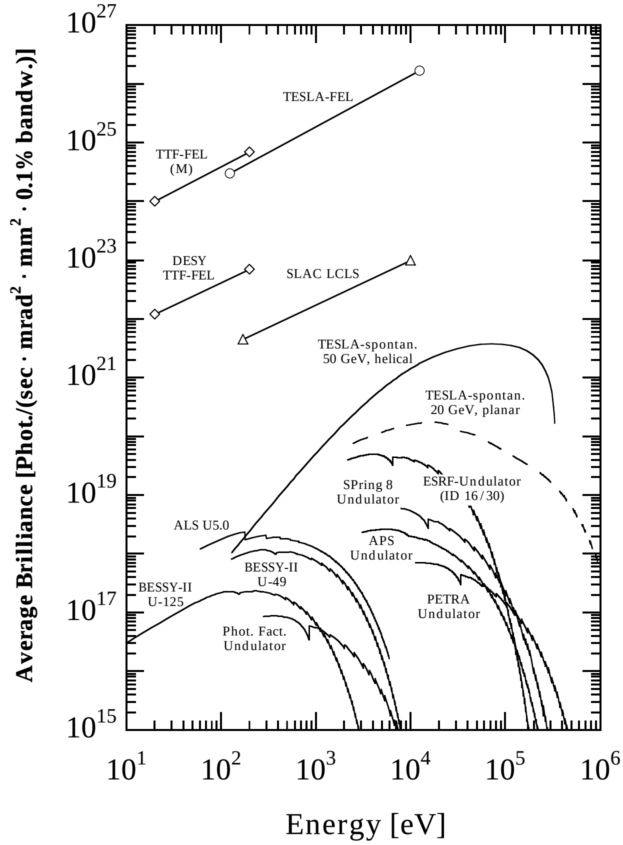

Figure 2: Spectral average brilliance of XFELs and various third generation synchrotron radiation sources

cathode where electrons are still non-relativistic, we choose a bunch charge of 1 nC. The performance of the state-of-the-art high intensity RF guns [9] at LANL and BNL serves here as a solid reference. LANL reached 2π mm-mrad at 1 nC and BNL 1π at 0.5 nC. 10 kA peak current means a 0.1 ps FWHM bunch length. In order to reduce space charge force at cathode, we use some 8 ps long laser pulse. Then bunch compression is necessary. A four-stage compression scheme has been worked out for XFEL while the first two stages for TTF FEL. Magnetic chicanes are used for the first two compressors, which are supposed to bring the rms bunch length from 2 mm down to 0.25 mm. Coherent synchrotron radiation (CSR) appears to be no longer negligible at such short bunch lengths, for it is now well above the cut-off of the beampipe. The shielding of CSRs is achieved by reducing the vacuum chamber height so that the trade-off between CSRs and wake fields reaches its optimum [15].

With λ_γ being radiation wavelength, λ_u undulator period, γ the relativistic factor, and K the undulator parameter, we have for planar undulators

$$\lambda_\gamma = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2}). \tag{2}$$

Let $K = 1$ and $\lambda_\gamma = 6$ nm, the undulator period will be around 2.5 cm. It is known that in order to increase the radiation power, a large K is desired. But this again means a long radiation wavelength. Since short wavelength and high radiation power are contradictory, we choose $K = 1.27$ and $\lambda_u = 27.3$ mm with mechanical constraints taken into account.

Energy spread should be well maintained within a certain limit, because the radiation spectrum width will then be doubled (see Eq. 2), which may eventually kill the phasing condition and finally the lasing process. An intra- and inter-bunch energy spread of 0.1% rms is then specified.

Beam quality is the key to a successful SASE lasing. As regards single bunch dynamics, TESLA is the optimal choice for its long wavelength, for longitudinal and transverse wake potentials scale with structure radius a and bunch length σ_s in the following way [10]:

$$W_{||} \propto \frac{1}{a^2\sqrt{\sigma_s}}, \quad W_\perp \propto \frac{x\sqrt{\sigma_s}}{a^3}. \tag{3}$$

Note that a scales in turn linearly to the RF frequency. TESLA FEL adopts a multibunch operation. For the multibunch dynamics, the long range interaction of bunches with higher order modes (HOMs) can be well suppressed due to the low HOM loss parameters. Tracking simulations show that a quite loose tolerance for the alignment can be specified without beam breakup (BBU): 0.1 mm rms for BPMs and quadruple magnets and 0.5 mm rms for cavities. These numbers are about 50 times larger than what an X-band machine would allow for. In addition, the long RF pulse of a few ms can generously accommodate a long bunch train, which makes handlings easy at a bunch-to-bunch level.

Figure 3 shows the TTF FEL phase I beamline layout. It is composed of three TESLA cryomodules, each capa-

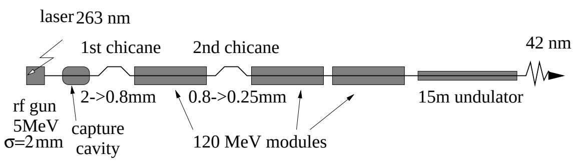

Figure 3: Beamline layout of the TTF VUV FEL phase I

ble of providing 120 MeV energy gain at 15 MV/m. The sophisticated superconducting Nb cavity processing techniques ensure us that the 15 MV/m accelerating gradient will be a routine production in the near future. In fact, from the currently existing 16 cavities [1], 13 of them reached an accelerating gradient higher than 20 MV/m, with one being even as high as 28.5 MV/m at $Q_0 = 5.8 \times 10^9$. This number already exceeds the TESLA design value of 25 MV/m at $Q = 5 \times 10^9$.

3 THE RF GUN

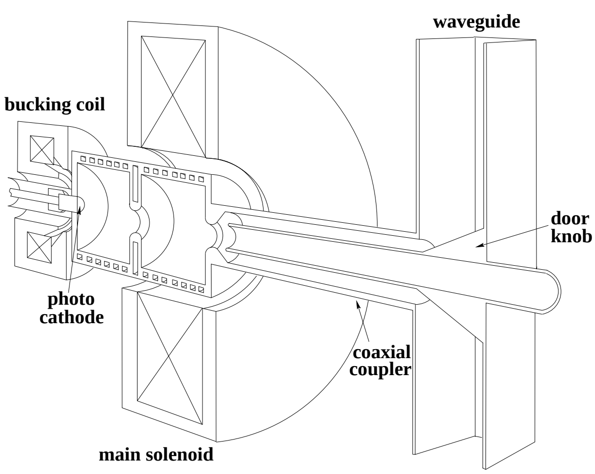

Figure 4: Cross sectional view of the RF gun, showing the one and half cell gun body, the main focusing solenoid and the bucking coil used for imposing the Neumann's boundary condition at the cathode plane for emittance compensation. The RF power is fed through the coaxial line via the waveguide-coaxial line door-knob transition. Due to its cylindrical symmetry, deflecting modes should be suppressed to the minimum.

The gun arrangement is shown in Fig. 4. At lower energies, space charge force plays a major role. Thanks to the space charge compensation scheme [11], a high quality beam of $\epsilon^n_{x,y} = 0.9\pi$ mm-mrad, $\epsilon_s = 27$ mm-keV, and $\sigma_s = 1$ mm seems to be achievable according to extensive simulations (Fig. 5). It is shown that wake field inside the gun can be neglected [12].

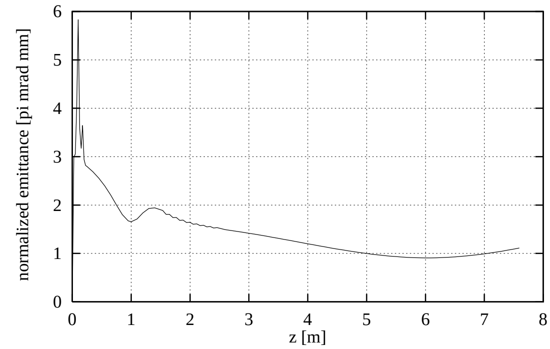

Figure 5: Transverse emittance development along the beamline simulated with PARMELA. Simulation settings: 1 nC bunch, 8.76 ps FWHM laser pulse length, 1.5 mm bunch radius, cathode peak electric field 50 MV/m, focusing B field 2080 G with the maximum at 12 cm from the cathode plane, injection RF phase -58^o off-crest, 10,000 macro-particles, 25 MV/m accelerating gradient for the capture cavity, which is placed 1.4 meters from the cathode. The minimum emittance of 0.9 π mm-mrad is reached at about 6 meters. $z = 0$ is the cathode plane.

The driving laser uses Nd:YLF as the active medium [13]. A train of 800 laser pulses at 1 MHz repetition rate has been acquired. Each pulse is 8 ps long rms with 5 μJ. A reduction of rms length down to 3.5 ps should be obtained in the near future [14]. To favor a better emittance compensation, an even shorter laser pulse is aimed at. The cathode material is Cs_2Te with a few percent quantum efficiency (QE). With QE = 1%, only half μJ will be sufficient to generate 1 nC charge in one bunch [2]. A cathode preparation system has been designed such that changing cathodes can be performed without breaking vacuum. The gun can provide a maximum energy gain of 5.3 MeV at 50 MV/m at the cathode. Table 1 lists the main parameters of the gun. To fully utilize the RF focusing capability and freeze the emittance as quickly as possible, a single TESLA 9 cell cavity (capture cavity in the TESLA jargon) is placed behind the gun at the location where the emittance reaches its minimum. At this stage, we obtain the following beam parameters: rms $\epsilon^n_{x,y} = 0.9\pi$ mm-mrad or 0.7π (10% collimated off), $\epsilon_s = 27$ mm-keV, $\delta_E = 0.13$%, and $\sigma_s = 1.06$ mm.

4 THE BUNCH COMPRESSORS

A total of four stages of compression are needed in order to bring the initial bunch length of 2 mm rms down to 25

[1] It is actually 26 cavities in total. Since it has been known that ten of them are either improperly welded or with material contaminations, they should therefore be ruled out in the quality statistics.

[2] The driving laser will also be used for the TTF operation, which requires 8 nC per bunch.

microwave properties	
frequency	1.3 GHz
accelerating mode	E01-π
nearest monopole mode	E010
frequency difference E01π-E010	4.58 MHz
quality factor Q_0	22600
bandwidth	58 kHz
at 50 MV/m peak	
stored EM energy	12.5 J
Ohm loss (within RF pulse)	4.5 MW
beam dynamics properties	
energy gain	5.3 MeV
bunch charge	1 nC
single bunch energy	5.3 mJ
average beam power (within RF pulse)	57 kW
solenoid strength	2080 G
laser injection phase	-58^o off-crest

Table 1: Gun parameters for the TTF FEL phase I

μm rms for the 1 Å lasing. For the TTF FEL phase I, two stages of compression are initially designed in order to get the bunch length from 2 mm down to 0.25 mm. The first should compress the bunch from 2 mm to 0.8 mm, the second to 0.25 mm. As seen above, after the capture cavity the bunch is already 1 mm short. We are eventually able to get rid of the first compressor. This may bring another benefit to the emittance preservation along the beam transport line. Some 30% reduction of emittance dilution due to space charge along the beamline can be achieved [12].

In the second compressor, since the bunch length is getting shorter, the coherent part of SR comes well above the cutoff frequency of the beampipe. Simulations [15] show that by properly reducing the height of the vacuum chamber to 8 mm the intra-bunch energy spread growth can be kept below 0.04% and the emittance dilution well under control.

5 THE MAIN LINAC

The main accelerating structure is composed of three TESLA superconducting cryomodules, each consisting of eight TESLA 9 cell cavities in a superfluid He bath (2K). With 15 MV/m nominal operation gradient for the TTF FEL phase I, a total of 390 MeV energy gain is expected. Due to the low frequency, i.e. the big geometry, the wakes are considerably small. For a bunch of σ_s =1 mm, $W_{//\rm max}$ is only 17.8 V/pc in a 9 cell TESLA cavity whereas in an S-band 180 cell structure, it is 600 V/pc (see e.g. [6] p987). The HOM power level is very low due to the small loss parameters for most HOMs. For the phase II, an accelerating gradient of 25 MV/m is planned.

6 THE UNDULATORS

To achieve SASE lasing at short wavelength, the undulator is one of the most critical components. Tolerance becomes very tight. There are two types of errors which may destroy the lasing process. One is transverse beam deviation from the straight line of radiation where electromagnetic interaction with the bunch takes place; The other the longitudinal phase shake. For a beam size of only a small fraction of mm, a tolerance of 10 μm [16] is mandatory at least over one undulator module length of 4.5 meters in order to maintain the gain reduction below 15%. This is translated to an integrated field error of 15 Tmm^2 at 300 MeV.

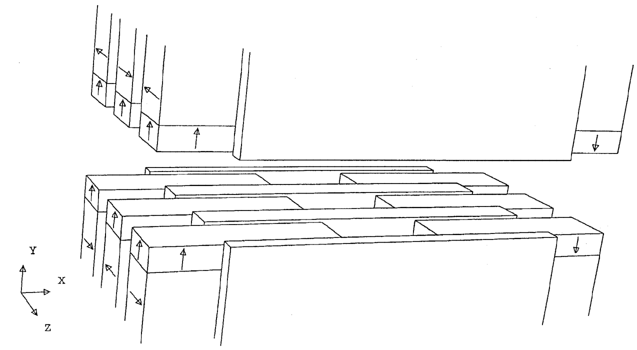

Figure 6: Perspective view of $1\frac{1}{2}$ periods of the so-called four-magnet focusing undulator (4MFU) which combines dipoles and quadrupoles. They are interlaced with each other. The blocks marked with arrows are permanent magnets. The rest are soft-iron poles.

number of undulators	3
length of undulator	4.5 m
period length	27.3 mm
peak B strength	0.5 T
rms $\Delta B/B$	$< 4 \times 10^{-3}$
number of quads per undulator	10
length of quadruple	136.5 mm =5 periods
gradient	12.5 T/m
distance between quads	480 mm
mechanical misalignment	$< 50\mu$m
at 300 MeV	
focal length	0.59 m
βmax	1.9 m
βmin	0.9 m
phase adv. per FODO cell	42^0
betatron wavelength	8.8 m

Table 2: Undulator parameters for the TTF FEL Phase I

For the TTF FEL phase I, a planar undulator using a combined function focusing arrangement has been designed and fabricated (Fig. 6). The rms mechanical tolerance is about 50 μm. With the delicate fine tuning mechanism to every single dipole and quadrupole [17], the tight 50 Tmm^2 can be maintained [18]. An active beam-based alignment procedure [19] [20] has been worked out, which is supposed to suppress lateral beam wandering down to the 10 μm limit. The main parameters of the undulator for the TTF FEL phase I can be found in Table 2.

7 THE LASING PROCESS

The SASE lasing bears a strong stochastic behavior, for it is starting from a random microbunching by the just-in-phase spontaneous radiations within the undulator bandwidth. A two-stage SASE scheme is proposed for the TESLA FEL [21], which reduces the lasing bandwidth considerably. As consequence, the brilliance is also increased by the same factor.

There are various computer codes available (for references, see e.g. [5]-[8]) for the SASE lasing process simulation. The characteristic of uncorrelated radiations from pulse to pulse can be clearly seen in Fig. 7. Within a tiny

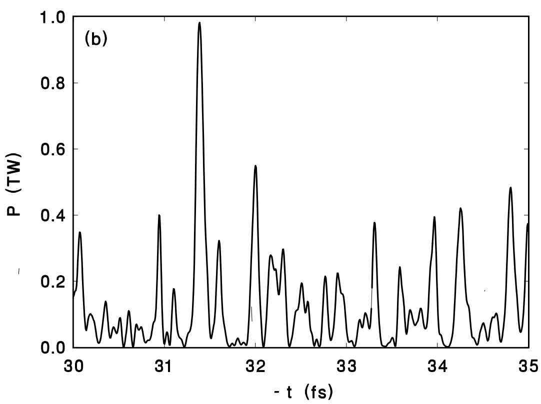

Figure 7: A zoom-in view of the temporal structure of a 180 fs long radiation pulse near the saturation point for a 1 Å FEL. It is simulated with a one-dimensional linear code [22].

fraction of the bunch length, the radiations may be well correlated. Such photon burst is usually referred to as superradiant [23]. From burst to burst, there exists no apparent phase correlation.

8 THE TTF FEL GUN TEST STAND

The proof-of-principle FEL test facility as described above is now under way at DESY at the TESLA Test Facility (TTF). The TTF HEP and TTF FEL beamline differs only in their guns. The rest of the facility will be more or less the same for the two operation modes. The former has a high charge but high emittance, while the latter low charge and low emittance. The first gun for the TTF FEL has been brazed and a low power RF measurement has been performed, showing a good agreement with the simulation results. A test stand, consisting of the gun, focusing and bucking solenoids, a dispersion section, and some diagnostic ports for pepper-pot and Faraday-cup, is near its completion. An initial hot beam test on the gun is scheduled this summer.

9 REFERENCES

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