THE VUV FREE ELECTRON LASER
BASED ON THE TESLA TEST FACILITY AT DESY

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

Abstract

A Free-Electron Laser (FEL) is under construction at DESY in Hamburg, aiming at short wavelengths in the VUV region. It makes use of the TESLA Test Facility (TTF), a superconducting linear accelerator now under construction at DESY in the framework of the TESLA collaboration. Its purpose is to provide the technical basis for TESLA, a superconducting, high-efficiency, high-gradient linear e+/e- collider with integrated X-ray laser Facility. The concept of a superconducting linac makes it possible to choose a relatively small accelerating rf frequency (1.3 GHz) and a large duty cycle (0.01). As a consequence, the TESLA linac is indeed exceptionally well suited for a short-wavelength Free-Electron Laser: Excellent beam quality, mandatory for a high-gain, short wavelength FEL, can be maintained during acceleration due to small wake fields. A large variety of pulse train patterns can be provided to serve various needs of potential users. The VUV FEL at the TTF comes in two phases, which are both approved. Phase 1 is the proof-of-principle experiment to demonstrate the Self-Amplified-Spontaneous-Emission (SASE) principle at wavelengths down to 42 Nanometers and to cultivate the technology necessary, such as small emittance photoinjectors, bunch compressors, precise undulators, and appropriate beam diagnostics. It will come into operation during 1999. Phase 2 aims at 6 Nanometers and provides photon beams for users.

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 even medical diagnostics. This rapid progress was driven by the development of new, increasingly brilliant sources based on electron storage rings. We believe that 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]). The reason is that 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 "microbunching", coherent emission at the resonant wavelength sets in which results in an exponential growth of the power of the radiation field (high gain mode):

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

Similar to synchrotron radiation sources, there is no fundamental limit in the choice of the photon wavelength. 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 $K = eB_u\lambda_u /2\pi mc$ 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 are 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, enery spread) good enough and an undulator long enough to reach the power saturation level within a single passage. At the satuaration length $L_{sat} \approx 4\pi\, L_{gain}$, the electrons run out of resonance due to their energy loss. For a schematic, see Fig. 1.

Also, if the desired wavelength is very short, there is no conventional laser to provide the "initially existing radiation field". Instead, one may consider the undulator radiation radiated spontaneously in the first part of the undulator as an input signal. FELs based on this principle of Self-Amplified-Spontaneous-Emission (=SASE) [2,3] are presently considered the most attractive candidates to

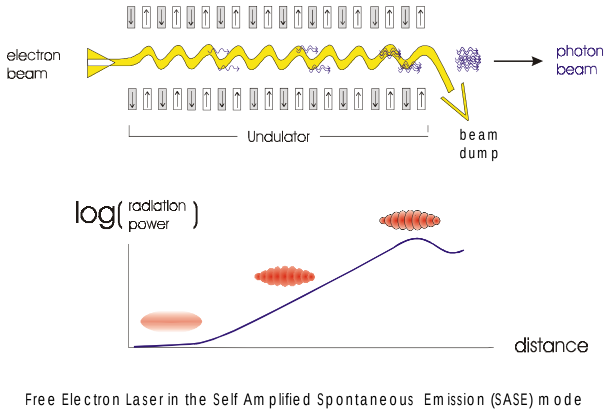

Fig. 1. Schematic drawing of an FEL operating in the "Self Amplified Spontaneous Emission = SASE" mode. The peak current in the electron bunch is very high and the undulator is long enough, so that power saturation is reached during a single passage starting from noise.

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. 2) 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 [7,8].

2 THE TESLA FEL CONCEPT

TESLA aims at a 500 GeV e+/e- collider with integrated X-ray laser Facility [6]. 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

It is understood that the ambitious goal of an 1 Å FEL cannot be achieved in a single step. Instead, three steps are foreseen:

1. **TTF FEL Phase 1** (approved) [9]: A SASE FEL experiment at wavelength down to 42 nm using the 390 MeV TESLA Test Facility (TTF) at DESY[12], see Fig. 3. 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.
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. 4. 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]. Table 1 summarizes main parameters of both electron and photon beams.
3. **TESLA** linear collider with Integrated X-ray Laser (in its technical design phase) [6,14]. If large field gradients are desired, even a superconducting linac has to operate in a pulsed mode. That's why there is enough 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 indeed utilize a linear collider installation for driving an X-ray FEL without mutual interference.

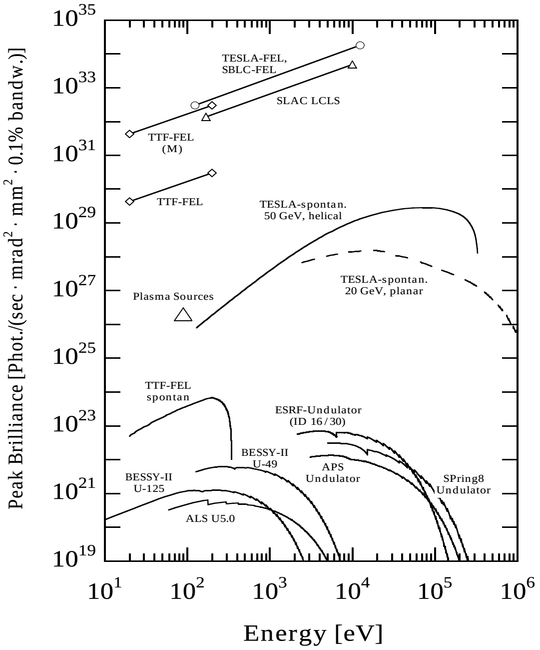

Fig. 2. Spectral peak brilliance of short-wavelength FELs compared with third generation radiation sources and plasma lasers. For comparison, the spontaneous spectrum of an X-ray FEL undulator at 20 GeV is also known.

Regarding preparation of 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 [15,16], bunch length compression by magnetic chicanes including control of coherent radiation effects [17], acceleration without beam degradation [18], and long undulators combined with a periodic FODO lattice [19,20].

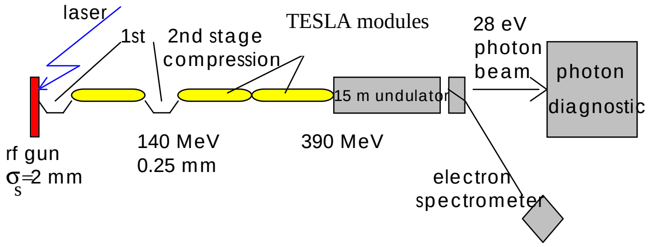

Fig. 3: Schematic layout of phase 1 of the SASE FEL project based on the TESLA Test Facility at DESY.

Table 1: Main parameters of the TESLA Test Facility FEL (TTF FEL)[10]. The insertion device is a planar hybrid undulator. These values should be used as a guideline only since experimental experience has still to be gained in this wavelength regime.

Parameter	**Units**	**Value**
beam energy	GeV	1.000
λ_{ph} (radiation wavelength)	nm	6.4 (193 eV)
λ_u(undulator period)	mm	27.3
effective undulator length	m	25
rms beam size	mm	0.05
ε^n (normalized emittance) in the undulator	π mrad mm	2.0
peak electron current	A	2490
No. of electrons per bunch		6.24E+9
No. of photons per bunch		4E+13
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
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

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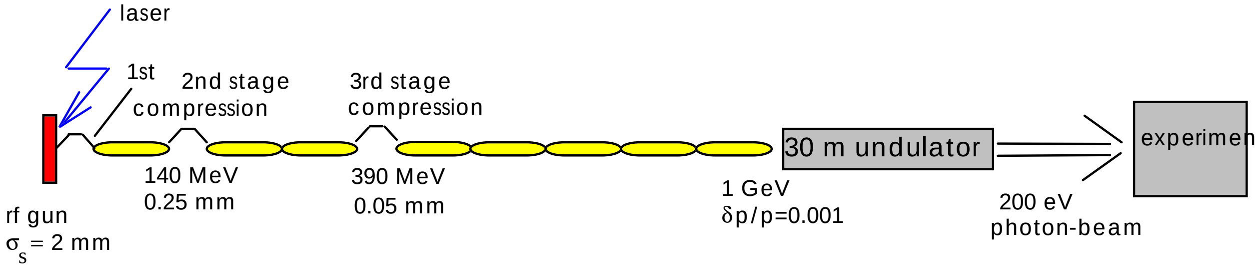

Fig. 4. Schematic layout of phase 2 of the SASE FEL project based on the TESLA Test Facility at DESY. The linac consists of 8 TESLA modules, each 12.2m long. The over-all length of phase 2 is some 300 meters.