THE TESLA XFEL PROJECT

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Abstract

The overall layout of the X-Ray FEL to be built in international collaboration at DESY will be described. This includes the envisaged operation parameters for the linear accelerator that will use TESLA technology. The different subsystems of the XFEL are described. A summary of the status of the preparation work will be given.

INTRODUCTION

X-rays play a crucial role in the study of structural and electronic properties of matter on an atomic scale. With high-brilliance X-ray sources high-resolution imaging and the observation of very fast chemical processes become possible. A high-brilliance X-ray free-electron laser (XFEL) based on linear accelerator technology using the principle of self-amplified spontaneous emission (SASE) appears to be the most promising approach [1, 2]. Since the high electron beam quality required by the SASE process presents challenges to the linear accelerator community, SASE test facilities in the visible and ultra-violet wavelength range were build during the last years [3]. Recent results have demonstrated the viability of injector systems, and longitudinal bunch compression schemes. Proof of principle experiments demonstrated that the physics of SASE FELs is well understood [4]. The TESLA Test Facility (TTF) FEL at DESY was used to establish first experiments using the photon beam of such a facility [5].

THE EUROPEAN XFEL

In 2003 the German Federal Ministry of Education and Research decided to support a European XFEL with 50% of its total costs of 684 M€ (basis year 2000). This decision was based on a principle layout of the XFEL developed and published in 2002 [2]. Since then some modifications became obvious, and the layout was improved. However, the design parameters as well as the layout, as described in the following section, are still under discussion. While DESY is preparing the plan approval procedure, i.e. the legal framework, and therefore detailing the different sections of the XFEL installation, a number of accelerator experts and future users, nominated by their home institutes and the corresponding national funding agencies, are discussing the final layout in two groups: Science and Technology Issues (STI) as well as Administrative and Funding Issues (AFI). Both groups are going to come up with a common proposal and a memorandum of understanding by 2005.

THE TTF FEL PROVIDES THE BASIS FOR THE EUROPEAN XFEL

The design of the proposed European XFEL facility is strongly based on the experience with the TESLA Test Facility FEL. During the last decade this accelerator was set up by the TESLA Collaboration in order to improve the superconducting accelerator technology [6]. The technology for the superconducting variant of a High Energy Linear Collider was established. In parallel to this, a proof of principle experiment for SASE FEL physics in the ultra-violet was carried out. First user experiments validated the scientific use of such a facility. Since fall 2003, the test facility was extended by adding more accelerator modules as well as by increasing the undulator length. After its commissioning (start late summer 2004) the facility, now named VUV-FEL, will deliver photon beams of high brilliance at wavelengths down to 6 nm. User operation as well as further SASE FEL studies will support the final design of the European XFEL.

The VUV-FEL Layout

The VUV-FEL includes basically all the subsections and components of the proposed XFEL (see also Fig. 1):

- An RF photoinjector producing high brightness electron beams with μm emittance (normalized) at kA peak currents.
- A superconducting booster accelerator section to get ultra-relativistic electron beam energies above 100 MeV allowing for a strong suppression of Coulomb forces in the space charge dominated electron beam transport.
- A longitudinal bunch compression enlarging the peak current in order to get saturation of the SASE process within an undulator of reasonable length (typically 30 m).
- The acceleration to the finally needed beam energy that determines the wavelength of the produced SAS radiation.
- Photon beam transport and diagnostics at short wavelength. The VUV-FEL will be operated down to 6 nm wavelength.

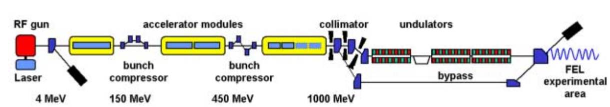

Figure 1: Layout of the VUV-FEL

The Layout of the European XFEL

The design parameters of the European XFEL are given in table 1. The performance goals for the electron beam are based on detailed simulations for the SASE FEL process at Ångström wavelength. The technical parameters of the accelerator sections are described below.

Table 1: XFEL Design Parameters

Performance Goals for the Electron Beam	
Beam Energy	20 GeV
Emittance (norm.)	1.4 mrad × mm
Bunch Charge	1 nC
Bunch Length	80 fs
Energy spread (uncorrel.)	2.5 MeV rms
Main Linac Section	
Energy Gain	0.5 to 20 GeV
Linac Length	approx. 1.4 km
Inst. Accelerator Modules	116
Installed Klystrons	29
Beam Current	5 mA
Beam Pulse Length	0.65 ms
Repetition Rate	10 Hz
Average Beam Power	650 kW
Performance Goals for SASE FEL Radiation*	
photon energy	12.4 – 0.2 keV
wavelength	0.1 – 6.4 nm
peak power	24 – 135 GW
average power	66 – 800 W
number photon per pulse	1.1 – 430 × 10^{12}
peak brillance	5.4 – 0.06 ×10^{33} **
average brillance	1.6 – 0.03 ×10^{25} **
* see Supplement to the XFEL TDR [2] ** in units of photons / (s $mrad^2$ mm^2 0.1% b.w.)	

The basic accelerator layout is illustrated in Figure 2. Two parallel injectors produce and accelerate the electron beam before combining it at roughly 100 MeV. A short accelerator section at a higher harmonic RF frequency is then used for the optimisation of longitudinal beam dynamics. This section is followed by a booster linac increasing the energy to 500 MeV. At this energy the electron bunches are compressed down to 20 µm, corresponding to approx. 5 kA. A detailed description of this process is given in Ref. [7]. The main linac uses 116 accelerator sections or modules grouped in 29 RF stations. The operating gradient is 23 MV/m. Twelve spare modules, i.e. three RF stations, are included in the design in order to guarantee the overall availability of the installation in case of failures.

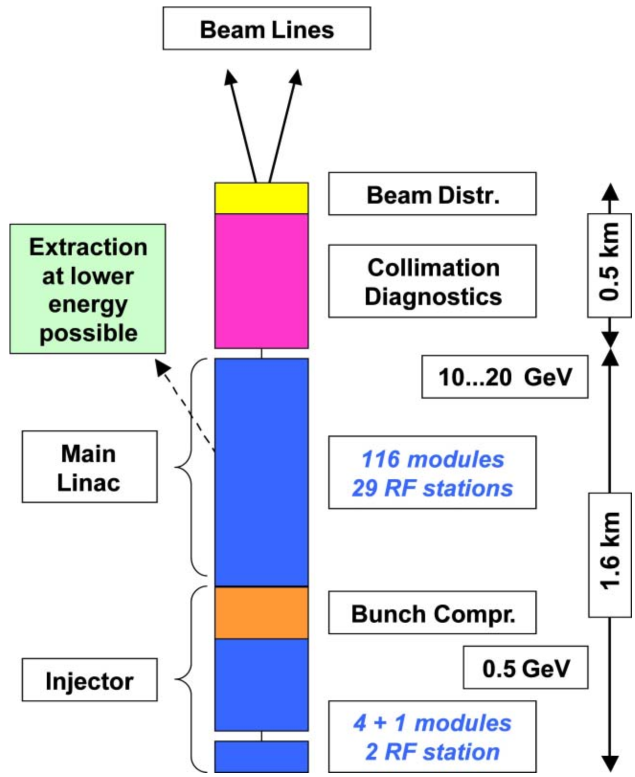

Figure 2: Basic Layout of the XFEL Accelerator

Since the superconducting accelerator technology features continuous wave (no duty cycle) operation of the linac, this mode of operation is under discussion for most of the upcoming FEL projects. For the XFEL a simple analysis of the required cryogenic power gives that CW is only of interest at clearly reduced final beam energy. At the design gradient of 23 MV/m the needed cryogenic power would even exceed the one of the proposed 30 km long superconducting linear collider. Nevertheless, at an accelerating gradient of about 7 MV/m corresponding to about 7 GeV final beam energy, the CW operation of the linac becomes more reasonable. For a continuous wave operation of the XFEL this of course would require also CW operation of the electron beam source, i.e. the injector. Here extensive R&D is needed. Some promising results are known [8]. Assuming that as a result of some longer term developments the possibility of Ångström FEL radiation at lower beam energies comes in reach, the consequence for the layout of the XFEL is obvious: the possibility to realize the CW option in a later phase of the project should be included. This will be done.

Parameter flexibility with respect to the time structure of the photon beam arriving at the undulators is a strong request of the future users. Defined by the different experiments the linac should be able to deliver beam with

- Homogenous filling
- Homogenous filling with variable number of bunches
- Homogenous filling with variable bunch distance
- Homogenous filling with variable bunch distance and number of bunches
- Sub-trains with variable distance and bunch number
- Pilot bunches ahead
- Pump and probe (two bunches spaced by one / a few RF buckets)
- Wavelength variation of a few percent inside a bunch train, i.e. energy variation

In order to generate these different patterns either the electron beam source, i.e. basically the laser driving the RF gun can be used or a somewhat sophisticated beam delivery / kicker system is needed. While in the first case the Low Level RF control of the accelerator sections has to take care of different beam loading conditions, the delivery system includes on the other hand challenging switching devices. A combination of both is under study.

TECHNICAL ISSUES OF THE XFEL

As stated above the XFEL strongly benefits from the successful operation of the TTF-FEL as well as from the commissioning of the VUV-FEL. However, some R&D is required in the different sections of the accelerator.

The Injector

The performance goal of the XFEL injector is given in Table 2. The energy at which the goal has to be fulfilled should be high enough (about 500 MeV) to overcome space charge forces in the succeeding linac sections.

Table 2: Performance Goals for the XFEL Injector

Emittance (norm.)	1.4 mrad × mm
Bunch Charge	1 nC
Bunch Length	80 fs
Energy spread (uncorrel.)	< 2.5 MeV rms
Beam Energy	500 MeV

The R&D work done so far by the TESLA Collaboration includes

- Cathode development at INFN Milano
- Simulation code development at DESY and Fermilab (FNAL)
- Design and construction of 3rd harmonic cavities at FNAL
- Experimental investigations at the A0 Photo injector at FNAL
- Injector operation at TTF I and TTF II
- Experimental investigations at the Photo injector Test stand PITZ at DESY Zeuthen [9]

The VUV-FEL as sketched in Figure 1 will validate the injector concept. The performance is expected to come close to the XFEL goals. In order to reach these parameters we have to

- increase the gradient on the cathode from 40 MV/m to 60 MV/m – this is scheduled for the next running period at PITZ
- improve the transverse and longitudinal laser profile further

Recent simulations have shown that a single-stage, two-chicane bunch compressor at about 500 MeV is the best choice [7]. Figure 3 illustrates the present XFEL injector layout.

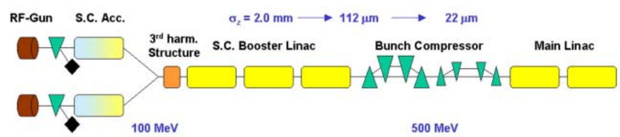

Figure 3: XFEL Injector Layout

The Main Linac

The accelerator sections to be used for the XFEL were developed in the frame of the TESLA R&D work. Each of these so-called accelerator modules houses eight superconducting 9-cell cavities operated at 1.3 GHz. The design of these modules has been primarily driven by the need to reduce costs and static cryogenic losses compared to existing superconducting cavity systems. At present the 3rd accelerator module generation is used for the 1 GeV extension of the TTF linac.

The TESLA 9-cell accelerator cavity is a standing wave structure of about 1 m length whose fundamental π-mode has a frequency of 1.3 GHz. The cavity is made from solid niobium and is bath-cooled by superfluid helium at 2 K. Each cavity is equipped with its own helium vessel; a frequency tuning system driven by a stepping motor; a coaxial RF power coupler; a pickup probe; and two higher-order mode (HOM) couplers.

The success of TESLA cavities is illustrated best by displaying the excitation curve, i.e. the quality factor as a function of accelerator gradient. Figure 4 gives the result of the latest development in cavity preparation: electro-polished surfaces allow for an accelerating gradient of up to 40 MV/m. A more complete description of the experience with the state-of-the-art cavity preparation as well as with the operation experience at the TTF Linac are given elsewhere [10, 11]. Higher accelerating gradients offer the potential to reach higher gradients and wavelengths below 1 Ångström.

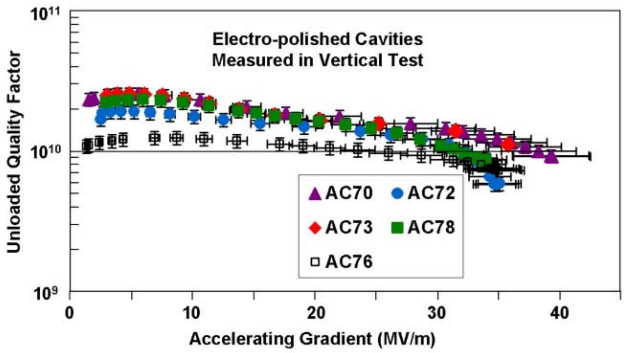

Figure 4: Electro-polished TESLA cavities allow for accelerating gradients of up to 40 MV/m.

Four accelerator modules, i.e. 32 cavities installed in about 50 m cryogenic section, form one RF unit. This unit will be supplied by one de-rated 10 MW multi-beam klystron as developed for the TESLA Linear Collider. The RF power needed for acceleration is 3.8 MW per klystron. We include a total of 25% overhead for amplitude stabilisation and power losses in the waveguide distribution system. The RF pulse length of 1.37 ms relates to the matched cavity Q_{ext} of 4.6×10^6 and the beam pulse length of 0.65 ms. The bouncer-type modulator supplying the klystron was developed in close collaboration with industry. The technology was tested at TTF. Industrial production can be assumed for the XFEL.

Waveguide RF distribution and Low Level RF control were investigated at TTF. The final layout will take advantage of the experience with the operation of the VUV-FEL.

Beam Switch Upstream of Undulators

Beam switching will be needed to fulfil the user requirements with respect to the photon pulse structure. Assuming several undulator beam lines one can use

- DC magnets delivering beam to one undulator at a time
- Slow switching from bunch train to bunch train thus resulting in a duty cycle for each beam line
- A high Q resonator producing a fixed bunch pattern but a full duty cycle
- Programmable fast kickers for selecting individual bunches; a very flexible but with respect to the kicker / pulser design challenging solution

The complexity of the beam distribution system is illustrated in Figure 5. Different undulators / photon beam lines are foreseen in two different phases of the XFEL project. At present a detailed layout taking the beam dynamic requirements into account is under study. It incorporates that the

- Emittance blow-up due to incoherent synchrotron radiation is below a few %
- Emittance dilution due to coherent synchrotron radiation stays below a few %
- Beam / particles with an energy deviation of less than 12% can be transported down to the beam dump
- Beam / particles with an energy deviation of less than 3% can be transported to the undulators without any degradation.

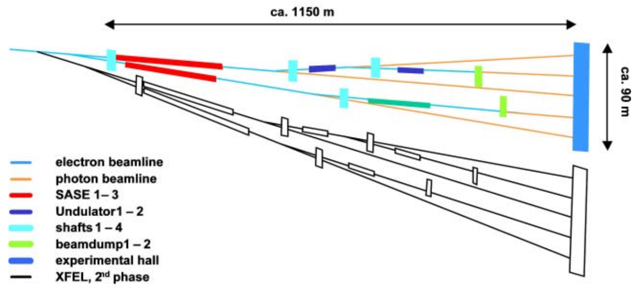

Figure 5: Electron beam distribution of the XFEL

In addition to the 'classical' distribution scheme other methods could be considered, e.g. shifting the phase between electron beam and radiation field, which would suppress the FEL gain. A delay of the electron beam by approx. 1 Å, namely λ/2 is needed. This can be easily achieved with a 4-magnet chicane between consecutive undulators [12].

XFEL SITE LAYOUT

In parallel to the R&D work towards industrial production of major components the preparations for the site are vitally important. In order to support the project approval procedure first design drawings of essential XFEL systems were made. Figure 6 shows the overall site layout as discussed. The XFEL starts on the DESY site, will pass urban areas approx. 30 m deep underground, and ends in an almost rural area which offers sufficient space for a new experimental site.

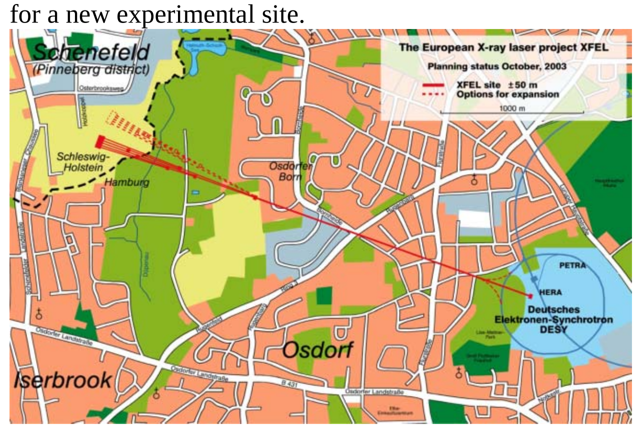

Figure 6: Overall Layout of the European X-Ray Laser Project XFEL (as from 2004)

Injector

Two injectors are installed in separate tunnel sections, mainly for availability reasons. While one is delivering beam to the succeeding accelerator sections, maintenance but also R&D is possible at the second one. This allows e.g. for the test of a CW electron beam source. RF modulators and other infrastructure are located outside the accelerator tunnel. Operation of the first cavities downstream of the RF gun at their design gradient is a prerequisite for high electron beam quality.

XFEL Tunnel

The main linac tunnel with its 5.2 m diameter is 15 to 30 m underground. It houses not only the accelerator but also klystrons, power supplies for magnets, and electronics. The modulators supplying the klystrons are located outside the tunnel. As seen in Figure 7, the preferred installation concept is suspension of the accelerator modules from the tunnel ceiling. This gives an easier access to klystrons and electronics, i.e. those components that need main attention during maintenance periods.

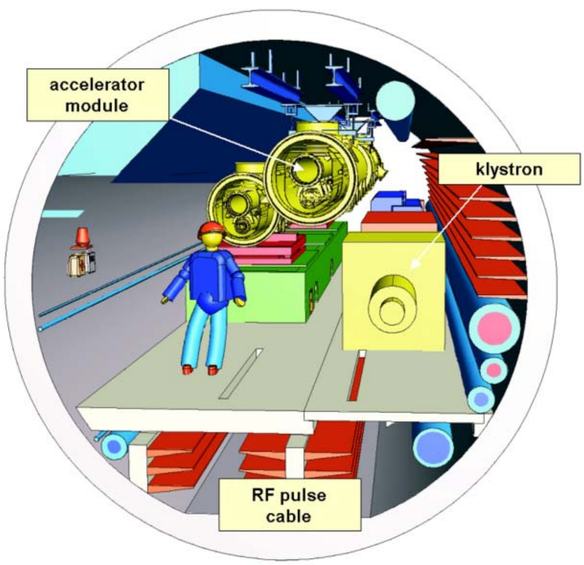

Figure 7: 3-d picture of the XFEL's main linac tunnel at the position of accelerator modules.

Cryogenic and RF Modulator Hall

The XFEL will take advantage of the DESY infrastructure. Two neighboring halls will house the cryogenic installation and all RF modulators. Helium tubes and pulse power cables will feed the linac tunnel from the injector end of the XFEL.

OUTLOOK

The 20 GeV s.c. linac based on the technology developed by the TESLA collaboration and successfully demonstrated at TTF / VUV-FEL is an ideal driver for the Free Electron Laser facility, offering a broad range of operating parameters in its baseline design. Future upgrade options can be included.

With the R&D work towards industrial production of major components and the preparations for the site and the legal procedure (plan approval procedure) well under way, we should be ready to go into construction phase in ~2 years from now.

ACKNOWLEDGEMENT

The XFEL is currently prepared by a group of experts being involved in the SASE FEL studies and TESLA R&D.

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