THE EUROPEAN XFEL PROJECT

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Abstract

The European XFEL project is a 4th generation synchrotron radiation facility based on the SASE FEL concept and the superconducting TESLA technology for a linear accelerator. In February 2003 the German government decided that the XFEL should be realized as a European project and be located at DESY in Hamburg.

The paper will give an overview of the overall layout and parameters of the facility, with emphasis on the accelerator design, technology and physics.

INTRODUCTION

X-rays have played for many decades a crucial role in the study of structural and electronic properties of matter on an atomic scale. With the ultra-high brilliant and sub-100 fs pulse length coherent radiation achievable with free electron laser X-ray sources the research in this field will enter a new era [1]. It will become possible to take holographic snapshots with atomic resolution in space and time resolution on the scale of chemical bond formation and breaking. Linear accelerator driven FELs using the principle of self-amplified spontaneous emission (SASE) [2] appear to be the most promising approach to produce this radiation with unprecedented quality in the Å-wavelength regime. The first facility of this type, using part of the existing SLAC linac, was proposed at Stanford and is now under construction [3, 4]. The XFEL was originally proposed as integral part of the TESLA project together with a 500 – 800 GeV e^+e^- Linear Collider based on superconducting RF (SRF) technology [5]. In a later update [6], the proposal was modified such as to build the XFEL with its own, separate linac for the benefit of flexibility regarding construction, commissioning and operation of the facility, maintaining the SRF technology identical to the collider linac and a common experimental site 16 km northwest from the DESY site in Hamburg. The German government decision in 2003 to go ahead with the XFEL as a European project and to postpone the decision on the collider led to a revision of the site, with synergy arguments for a common site no longer in effect. The new site layout has the XFEL linac starting on the DESY site, permitting to make optimum use of existing infrastructure, and the user facility in a rural area about 3 km west-northwest from DESY. The legal procedure to obtain permission for construction is in preparation and expected to be completed by end of 2005. The project organisation at the European level is ongoing. The final decision to move into the construction phase is expected for 2006. The construction time until beam operation will be 6 years.

The electron beam quality and stability required by the SASE process presents considerable challenges to the linear accelerator community. SASE test facilities in the visible and ultra-violet wavelength range were built and operated during the last years [7]. The results have demonstrated the viability of the challenging accelerator subsystems and the good understanding of the SASE process. In particular the successful operation of the TESLA Test Facility (TTF) linac and FEL at DESY provides a firm basis for the XFEL, regarding the SRF technology, beam dynamics and the FEL process [8] and the conduction of user experiments [9]. In its 2nd phase, just about to start, operation of the VUVFEL, designed for FEL radiation down to 6 nm wavelength, will continue to deliver a vast amount of experience as a pilot facility for the future project [10].

OVERALL LAYOUT AND PARAMETERS

The XFEL is laid out as a multi-user facility. In its 1st stage, it will have 5 undulator beam lines, 3 of which are SASE-FELs (two for the Å wavelength regime, one for softer X-rays), the other two for hard X-ray spontaneous radiation. Initially, 10 experimental stations are foreseen. The underground experimental hall has a floor space of 50×90 m^2 and more stations can be added later. The site allows to extend the user facility for more beam lines in a later stage (see Figure 2).

The undulator sections have a maximum total length of 250 m. Variable gap (min. 10 mm), 5 m long undulator segments are foreseen, which not only permits to independently adjust the photon energy within certain limits, but also facilitates the precise steering of the electron beam for optimum overlap with the photon beam [11].

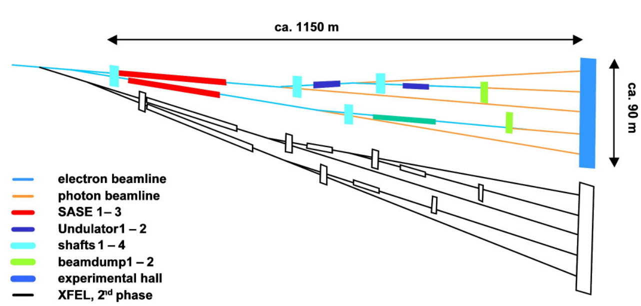

Figure 2: Layout of user beam lines (incl. extension).

An overview of the main XFEL parameters is given in Table 1.

Performance Goals for the Electron Beam	
Beam Energy	10 - 20 GeV
Emittance (norm.)	1.4 mrad · mm
Bunch Charge	1 nC
Bunch Length	80 fs
Performance Goals for SASE FEL Radiation	
photon energy	15 – 0.2 keV
wavelength	0.08 – 6.4 nm
peak power	24 – 135 GW
average power	66 – 800 W
number photon per pulse	$1.1 – 430 \cdot 10^{12}$
peak brillance	$5.4 – 0.06 \cdot 10^{33}$ *
average brillance	$1.6 – 0.03 \cdot 10^{25}$ *
* in units of photons / (s $mrad^2$ mm^2 0.1% b.w.)	

Table 1: XFEL Design Parameters

The main linac uses 116 12 m long accelerator modules with 8 superconducting cavities each, grouped in 29 RF stations. Twelve spare modules, i.e. three RF stations, are included in the design in order to guarantee the overall availability of the accelerator in case of failures. The linac is housed in a tunnel (Figure 3) 15 – 30 m underground. The klystrons are in the tunnel and connected to the modulators in an easily accessible surface building on the DESY site by 10 kV pulse cables.

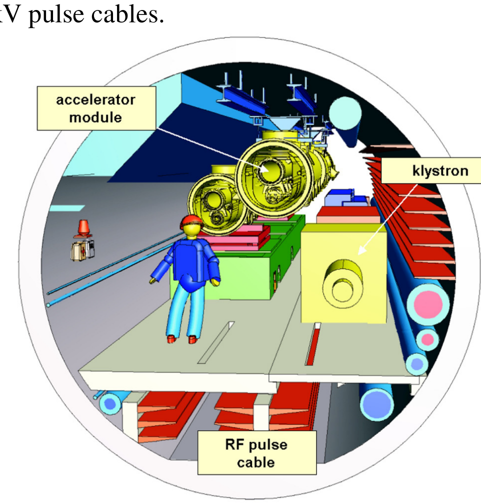

Figure 3: 3D drawing of the 5.2 m diameter main linac tunnel. The accelerator modules will be suspended from the ceiling.

The required klystron power per station is 4.8 MW, well below the maximum power of 10 MW of the multi-beam klystrons developed in industry for the TESLA project. This will not only cover the power needs for the above mentioned operation at higher energies, but also allow to operate the linac at higher repetition rates (and duty cycles) at lower energy (the main limitation then being the average power of the RF system).

SRF LINAC TECHNOLOGY

The XFEL linac is based entirely on the technology which was over the past years developed by the TESLA collaboration as the most essential part of the R&D programme towards a superconducting linear collider. The successful completion of the 1st phase of the TESLA Test Facility (TTF) has demonstrated that superconducting 9-cell Nb cavities can be reliably produced with the XFEL design performance of 23 MV/m. Stable beam acceleration at (or near) this gradient was also demonstrated with complete 12 m long accelerator modules, containing 8 cavities each, in the TTF linac [15]. The latest generation accelerator module #5, now installed in the upgraded phase-2 TTF/VUV-FEL (Figure 4), performed in RF tests at a gradient of 25 MV/m for all cavities simultaneously (higher for 6 out of 8 in single cavity RF tests) [16]. Several 10 MW multi-beam klystrons have been built by industry in France and operated at TTF at design specs. Prototypes from additional vendors are under development [17, 18]. Industrialisation of all linac components is one of the crucial tasks on the way towards construction of the machine.

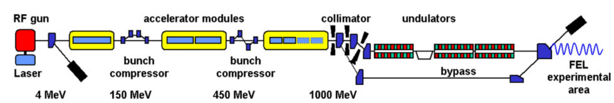

Figure 4: TTF-II and VUV-FEL layout

The continuing TESLA SRF R&D programme has by now delivered state-of-the-art cavities with a performance well exceeding the XFEL baseline requirements. With the electro-polishing (EP) method to improve the Nb surface quality, pioneered at KEK, five 9-cell cavities were tested at gradients of 35 – 40 MV/m [19].

INJECTOR & BUNCH COMPRESSOR

To optimise availability, there are two parallel injectors to produce and accelerate the electron beam before combining the beam lines at roughly 100 MeV (see Fig 5). The injector tunnels are shielded from each other, such that maintenance, repair or modifications of one of them is possible while continuing to operate the facility with the other. A short accelerator section at the 3rd harmonic RF frequency is then used for the linearization of longitudinal phase space. This section is followed by a booster linac increasing the energy to 500 MeV. At this energy the electron bunches are compressed by about a factor of 100 down to $\sigma_z \cong 22\,\mu$m, corresponding to approx. 5 kA peak current for 1 nC charge. A detailed description of this process is given in Ref. [20]. Operation in this extremely short bunch length regime presents considerable technical and beam dynamics challenges, for a recent overview of this subject, see ref. [21].

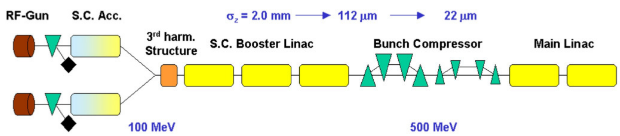

Figure 5: XFEL Injector Layout

Simulation results for the photocathode RF gun indicate that an rms normalised emittance of 0.9 mm·mrad is achievable (see ref. [22] for a recent update). The R&D for low-emittance electron beam sources has been performed within the TESLA collaboration and is supported by the EU Framework Programme 6. Beam tests of the latest version of the RF gun have been done at the PITZ test stand at DESY, Zeuthen [23], yielding a normalised emittance of 1.5 mm·mrad. Further improvements are expected by increasing the accelerating field on the cathode from 40 to 60 MV/m and optimising the homogeneity of the laser beam profile. The gun previously tested at PITZ has now been installed and successfully commissioned at the VUV-FEL [24].

The bunch compressor has in comparison to the earlier version [6] been simplified by going from a 3-stage to a single stage layout. This approach turned out to be more robust against the potential problem of the micro-bunching instability. The latter can lead to a strong amplification of initially small modulations in the longitudinal bunch charge distribution by coherent synchrotron radiation (CSR) and space charge effects, unless the uncorrelated energy spread is intentionally increased by ‘heating’ with a laser [25, 26]. The effect of CSR on the beam emittance is in the present layout strongly reduced by splitting up the magnetic chicane of the compressor into a first section with large momentum compaction (transfer matrix element R_{56}) and a second one with small R_{56}. The weak bends in the second section avoid excessive CSR at a position where the bunch becomes shortest. The residual emittance growth obtained from extensive beam dynamics simulations is of the order of 10%, well within the 50% total budget for emittance dilution from the source to the undulators. Further dilution in the downstream main linac is small as a result of very weak wakefields in the TESLA accelerating structures, so that the overall design includes a reasonable safety margin regarding the beam emittance requirements.

The large bunch compression ratio is inevitably connected with tight tolerances on timing, RF phases and amplitude of the gun and the booster section. The effects of jitter in these and other parameters on the FEL photon beam properties have been studied in model calculations [27]. Even with tight assumptions of 0.05°, 0.02% and 0.1 ps in RF phase, amplitude and gun timing jitter (rms) respectively, the fluctuations of photon pulse length and saturation power are not negligible and efficient photon diagnostics are likely required to monitor the beam and correlate variations with experimental data. An advantage of the SRF concept is the possibility to stabilise the RF parameters within a pulse by feedback. An alternative layout with 2 compressor stages is being investigated [28] to asses whether potential advantages regarding jitter tolerances would justify such a 2nd stage.

BEAM DISTRIBUTION

The XFEL linac can accelerate more than 3,000 bunches per RF pulse, serious beam dynamics problems related to higher order modes in the cavities are not expected [29]. User requirements regarding beam time structure will vary over a large range, from single or few bunches to partial or full trains per RF pulse. Generation of such patterns is possible at the source, at the end of the linac or by a combination of both. From the point of view of maximum flexibility a system using programmable fast kickers appears to be the optimum solution. Beam loading conditions in the linac could be quasi static, i.e. the same from pulse to pulse, and bunches could be distributed to different beam lines according to the needs of the respective experiments. The required switching devices are demanding, though, regarding jitter tolerances and reliability. The developments in this direction profit from the R&D work for the linear collider damping ring kickers which have more or less similar requirements. Recently, a very stable kicker pulser was developed at BESSY [30], which appears promising and will be further investigated in the future. In addition to switching the electron beam, it is also possible to switch the FEL process on and off by phase shifters, such that different photon pulse time structures can be generated in a beam line with a sequence of several undulators [31].

The beam transport lattice from the end of the linac to the undulators includes sections for diagnostics and collimation to protect the undulators from potentially large amplitude halo or mis-steered beam. A large momentum acceptance is foreseen so that energy modulation within a bunch train by up to 3% is possible. The lattice layout and the civil construction in the beam distribution region for the 1st phase of the user facility will also already take into account the possibility of later adding more beam lines.

Among the options to add features to the range of possible photon beam properties, very short pulses in the sub-fs regime appear very attractive for certain classes of experiments and could be generated by modulating the energy distribution in the bunch with a very fast laser just upstream from the SASE undulators [32, 33].

CONCLUSION

The 20 GeV linac based on the technology developed by the TESLA collaboration and successfully demonstrated at TTF / VUV-FEL is an ideal driver for the X-ray Free Electron Laser facility, offering a broad range of operating parameters in its baseline design and a considerable potential for future upgrades and options.

With the R&D work progressing 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 the construction phase in ~2 years from now.

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