THE EUROPEAN X-RAY FREE ELECTRON LASER PROJECT AT DESY

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Abstract

The X-ray Free Electron Laser XFEL is a 4th generation synchrotron radiation facility based on the SASE FEL concept and the superconducting TESLA technology for the linear accelerator. In February, 2003, the German Federal Ministry of Education and Research decided that the XFEL, proposed by the International TESLA Collaboration, should be realized as a European project and located at DESY/Hamburg. The ministry also announced that in view of the locational advantage, Germany is prepared to cover half of the investment and personnel costs for the XFEL. In the course of the last year work has concentrated on the following areas: setting up of an organizational structure at DESY for the preparation of the project, discussions with potential European partners on several levels, selection of a new site for the XFEL facility and the preparation of the 'project approval procedure'. The present status of the technical layout of the Linear Accelerator, the SASE Undulator and Photon Beam lines and the experiment stations will be presented.

BASIC DESIGN CONSIDERATIONS

The basic idea underlying the XFEL is the extension of the principle of linear accelerator based Self Amplification of Spontaneous Emission (SASE) Free Electron Lasers (FELs) to the hard X-ray (~1Å wavelength) regime. The ultra-high brilliant laser pulses with sub-100-fs pulse length and a large degree of coherence will allow to probe the dynamic state of matter with atomic resolution in space and time and to study non-equilibrium states and very fast transitions between different states of matter [1]. Compared to 3rd generation synchrotron sources the gain factors for the peak brilliance for the SASE lines and the spontaneous radiation exceed 10^9 and 10^4, respectively. Using superconducting Rf technology for the linear accelerator allows for a large flexibility in the electron bunch patterns.

TECHNICAL LAYOUT

The principle layout for the first stage of the XFEL facility is shown in Fig.1 [2], [3]. The electron beam is accelerated in a linear accelerator using superconducting Rf technology to approx. 20GeV and then distributed into several beam lines, This allows to use the electron beam for several FELs and spontaneous radiators and facilitates parallel operation of many experiments, including R&D on the light generation process and beam line hardware.

The SASE FELs cover the photon energy range between 200eV and ≤15keV in a continuous way. The emphasis is on the production of hard X-rays such that 1Å wavelength can safely be reached with conservative assumptions on the beam parameters.

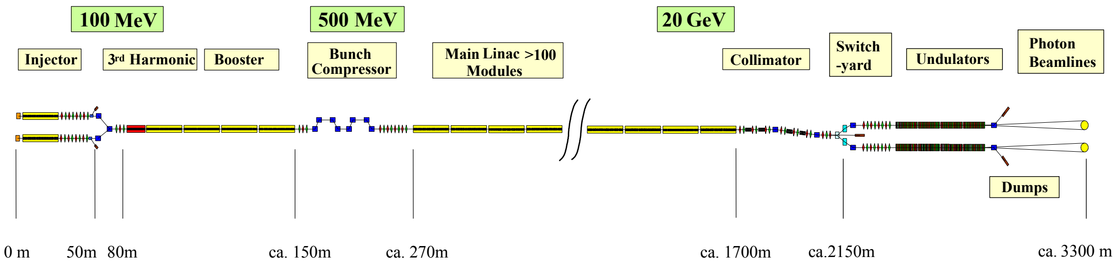

Figure 1: The principle layout of the XFEL facility

The overall length of the facility is 3.3km (2.15km for the linear accelerator complex including the beam collimation section and 1.15km for the undulator and photon beam lines). The length scales are largely determined by

- the required electron beam energy and the available accelerating gradient of the superconducting Rf structures
- the requirements of the machine optics in the beam distribution sections,
- the saturation length of the undulators

- provisions for spare space for future options (e.g. laser- or self-seeding) and
- the photon diagnostics and transport lines.

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 50×90m^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).

Table 1: XFEL Design Parameters

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
Energy spread (uncorrel.)	<2.5 MeV rms
Main Linac	
Acc. Gradient @ 20 GeV	23 MV/m
Linac Length	approx. 1.5 km
Inst. Accelerator Modules	116
Installed Klystrons	29
Beam Current (max)	5 mA
Beam Pulse Length	0.65 ms
# Bunches p. Pulse (max)	3250
Bunch Spacing (min)	200 ns
Repetition Rate	10 Hz
Max. Avg. Beam Power	650 kW
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 × 10^{12}
peak brillance	5.4 – 0.06 ×10^{33} *
average brillance	1.6 – 0.03 ×10^{25} *
* in units of photons / (s mrad^2 mm^2 0.1% b.w.)	

An overview of the main XFEL parameters is given in Table 1. The undulator parameters have been optimised for one Å wavelength at a beam energy of 17.5 GeV. This implies that at the nominal maximum beam energy from the linac of 20GeV at 23MV/m accelerating gradient, the ^{57}Fe line at 0.08nm, of interest for certain experiments, will be accessible.

ELECTRON 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 [4]. 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.

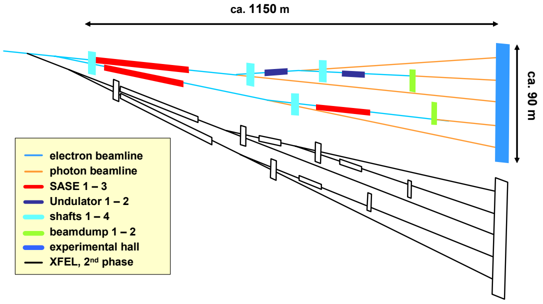

Figure 2: The 1st stage user beam line layout (coloured) and the possible extension.

The required switching devices are demanding, though, regarding jitter tolerances and reliability. 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 [5].

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 with 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.

PHOTON BEAM LINES

The generic layout for the undulator and photon beam lines is shown in Fig.3. Following the light generation in the undulator sections, a gasfilter section with photon monitoring is added that allows to tune the intensity of the photon beam. This is followed with a photon diagnostic section. Before entering the experimental hall, the photons pass through a mirror system, with e.g. a double crystal monochromator. After the monochromator, the photon beam is split into several beams that are transferred to a range of experiments in the experimental hall.

The undulator sections have a maximum total length of 250m. Variable gap (min. 10mm) type 5m 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 [6]. Typical Distances are ~650m between the exit of the undulator and the optical elements and ~200m between the optics and the experiment.

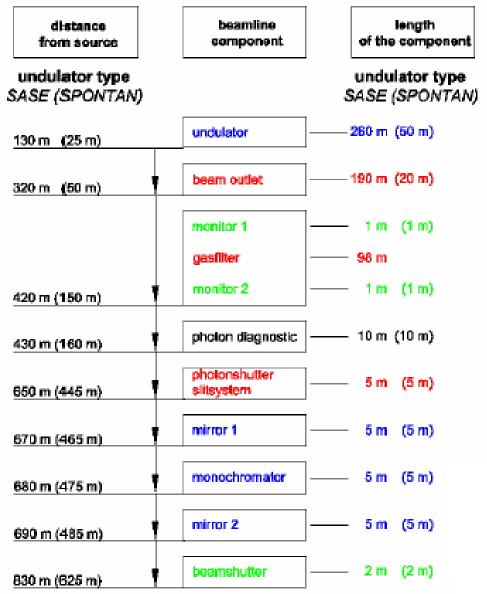

Figure 3: The generic layout for the undulator and photon beam lines

A generic layout of the experimental area at the end of a given photon beam line is shown in Fig.4. The area available for experiments is approximately 750 square meters for each of the five photon beam lines of the first stage of the XFEL facility.

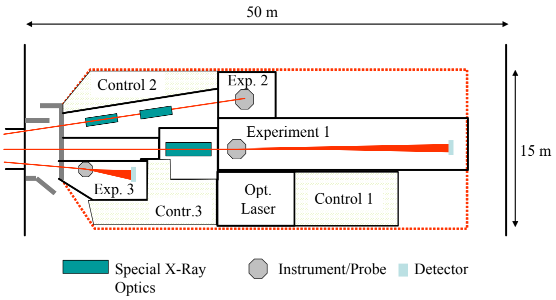

Figure 4: A generic layout of the experimental area at the end of one of the five photon beam lines of the first stage of the European XFEL facility

PARAMETER FLEXIBILITY

With conservative assumptions for the slice energy spread of the electron bunch (2.5MeV), the slice emittance (1.4mm mrad) and the size of the undulator gap (10mm) a wavelength of 1Å can be reached at a beam energy of 17.5GeV with a saturation length of approx. 140m. Improvements in the slice emittance or the energy spread at a given beam energy would allow a reduction of the saturation length or a reduction of the photon wavelength below 1Å at the same undulator length.

Furthermore, the expected higher performance of the superconducting cavities of the linear accelerator will permit to operate at even shorter wavelength, provided that the electron beam quality can also be further improved to guarantee saturation in the SASE FEL process.

The required klystron power per station is 4.8MW, well below the maximum power of 10MW of the multi-beam klystrons developed in industry for the TESLA project. This will not only cover the power needs for an 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).

In contrast to conventional linacs, with the superconducting accelerator technology even a continuous wave (CW, 100% duty cycle) operation of the linac is conceivable [3], although only at reduced energy/accelerating gradient in order to avoid excessive cryogenic load into the Helium at 2K. Such an option is not viewed as being part of the initial stage of the facility, but could become attractive if lower-emittance, high duty cycle beam sources become available [7], possibly in combination with advanced FEL concepts.

The superconducting linac allows for a wide flexibility in the generation of bunch train patterns. The nominal beam pulse length is 0.65ms with max. 3250 bunches per pulse at a spacing of min. 200ns. Depending on the requirements of the user community, single bunches or few bunches per pulse train are possible as well as bunch trains with varying bunch spacing.

PRESENT ACTIVITIES/STATUS

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 [8]. In a later update [9], 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 16km 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. The new site layout, sketched in Fig.5, 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 3km west-northwest from DESY south of the city of Schenefeld.

Project Approval Procedure

In Germany, the legal procedure necessary to prepare the civil construction and operation for such a large scale facility as the XFEL is the 'Project Approval Procedure'. The legal basis for such a procedure is a treaty between the Bundesländer Hamburg and Schleswig-Holstein which has been signed by the respective governments in July, 2004.

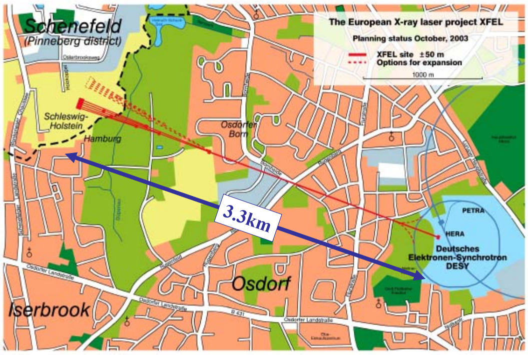

Figure 5: Sketch of the XFEL site near DESY

For the Project Approval Procedure a relatively detailed planning of the various underground and surface buildings and the construction and operation phases of the facility has to be performed. After the decision for the site in October 2003, the planning for the Project Approval Procedure has started. It is foreseen to prepare all necessary material describing the project by spring 2005. The examination of the planning information by a public authority will then take likely until the end of 2005 such that construction of the European X-Ray Laser Laboratory XFEL can start in the year 2006.

Towards a European XFEL

The project organisation at the European level is ongoing. A steering committee and two working groups, one on scientific-technical (STI) and one on administrative and financial issues (AFI), have been established early in 2004, with members from all European countries which are interested in participating in the project. The main task of these groups is to prepare the documents required for the technical definition and organisational structure of the project by 2005. The final decision to move into the construction phase is expected for 2006. The construction time until beam operation will be 6 years. The total project cost is estimated at 684 M€ (year 2000 price level), of which Germany will cover 50%.

A Memorandum of Understanding (MoU) regulating the preparatory phase for the construction of the European XFEL has been prepared by the presently participating countries and is expected to be signed before the end of the 2004.

The XFEL Project Group at DESY

In the summer of the year 2003 a project group was established at DESY in order to organise the preparatory work towards start of construction of the facility in 2006. The charge of this group thus covers the present intermediate phase of the project during which the organisation at the European level is in progress. The main tasks are the further optimisation of the overall design of the XFEL, starting from the supplement [9] of the TESLA Technical Design Report [8], the specification, prototyping, etc. of major technical components towards industrial production and the preparation of the site for the facility near the existing DESY site in Hamburg. While the group has at the start been formally arranged purely within the DESY laboratory, it is also thought to serve as an organisational structure to facilitate and integrate participation from outside collaborators in this intermediate phase, for the time being until a European project group has been established.

The DESY XFEL group is managed by a project leader, a deputy project leader and an administrative project coordinator. In order to structure the work, in total 37 work packages (WPs) have been defined. The WPs are grouped into 6 main topics as listed in Table 2.

Table 2: Work Package Groups for the organization of the preparatory work for the XFEL at DESY

WP group	Topic
01	Linear Accelerator
02	Accelerator Sub-systems
03	Photon Beam Lines
04	General Issues
05	Infrastructure
06	Site and Buildings

For each of the 37 WPs a person has been nominated as the coordinator in charge for this part of the work within the DESY laboratory. It is expected that responsibility for part of or entire WPs will be taken over by persons from outside DESY, once the project organisation develops from its present stage to the European level.

The project group holds regular weekly meetings. Participation via video by external groups can be easily arranged and has occasionally been used. In addition to the main weekly project meeting, a considerable number of other sub-group meetings, either on a regular basis or when required, take place (examples: preparations for the Project Approval Procedure for legal permission of construction, accelerator module group, beam dynamics group). A web site has been set up to serve as information platform among the participating groups and institutes [10].

CONCLUSION

The European X-Ray Free Electron Laser Laboratory will provide unprecedented opportunities for basic research with photons in the 1Å regime. The baseline design offers a conservative approach to reach this wavelength. It offers a considerable amount of flexibility and allows later incorporation of further developments in the photon generation scheme. The preparatory work for the XFEL is well underway at DESY and on the European level.

With the R&D work progressing towards industrial production of major components and the preparations for the site and the legal procedure (project approval procedure) well under way, the project should be ready to go into the construction phase in ~2 years from now such that the facility could be commissioned in 2012.

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