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SCIENTIFIC APPLICATIONS OF X-RAY FREE-ELECTRON LASER SOURCES

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Keywords: x-ray free-electron lasers, ultrafast dynamics, coherent diffraction, extreme conditions, coherent x-ray optics, x-ray instrumentation

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Present-day scientific applications using x-rays from synchrotron radiation sources show very high performance in a broad range of science areas. However, even the newest and most performing sources are limited intrinsically in their pulse duration, photon flux per pulse and coherence properties. A variety of scientific problems therefore cannot be investigated at present. Amongst these are the investigation of dynamics of matter and of extremely short-living states, both at ultrafast time-scales, and the imaging of nanoscale systems with atomic or at least sub-nanometer resolution. Recently proposed free-electron lasers (FEL) for x-ray radiation will provide radiation with many orders of magnitude higher peak brilliance. These sources promise to overcome the present-day limitations and will allow a broad range of new x-ray scientific applications.

For short-wavelength radiation of the order 0.1 nm using the self-amplifed spontaneous emission (SASE) principle is the most reliable way to generate high FEL gain [1-3]. The FEL process depends critically on the emittance of a high-energy electron beam of very high peak current that can be generated by linear accelerators only. Spontaneous emission of synchrotron radiation in a very precise undulator magnetic field is used to create an electro-magnetic field co-propagating with the electron bunch through the undulator. The interaction of the electro-magnetic field with the electron bunch leads to the characteristic exponential gain process. The emitted FEL radiation is characterized by typically 100 femtosecond duration, a peak flux of 10^{12} – 10^{14} photons per pulse, and high degree of coherence. The best appreciation of this combination of properties gives the peak brilliance of an XFEL reaching about nine orders of magnitude higher than present-day sources. As the FEL process starts from noise the radiation output shows statistical fluctuations in output power, temporal and spectral distribution. Experiments using FEL radiation therefore will require specific diagnostics of the radiation, in many cases on a shot-by-shot basis.

The first short-wavelength FEL facility, providing FEL radiation of 6-100 nm wavelength is FLASH at DESY, Hamburg [4-6]. The facility is operational since 2006 and provides FEL radiation for scientific experiments of a broad user community. At the same time many new developments in the areas of accelerator, FEL technology and scientific instruments are pursued at FLASH. The first facility operating in the hard x-ray range will be the LCLS at SLAC, Stanford, scheduled to start operation by 2009. Another hard x-ray facility, the European XFEL, launched in June 2007 and scheduled for first beam in 2014, is based on a super-conducting accelerator enabling acceleration of a large number of electron bunches during a single radio-frequency pulse [7]. Likewise the total number of x-ray pulses available to the experiments can be increased significantly (up to 30,000 per second). On the one hand, this significant increase in average brilliance compared to other FEL facilities enables new science, facilitates the parallel operation of many instruments and leads to improved stability of the electron beam. On the other hand, the high intensity and the high repetition rate lead to new requirements for x-ray optics and x-ray diagnostics. These requirements will be discussed in relation to the scientific instruments which have been proposed for the European XFEL facility.

X-ray FEL radiation in the photon energy regime from a few 100 up to 15000 eV will enable to address new scientific problems in the areas of physics, materials science, chemistry and biology. The particular properties of hard x-ray FEL radiation, these are the short wavelength, the short pulse duration, the high degree of transverse and longitudinal coherence and the high pulse intensities, will provide outstanding conditions for the investigation of ultrafast dynamics on the femtosecond level, of properties of nanoscale systems including biological samples and matter under extreme conditions energy density. In the lecture examples of proposed investigations and the current state-of-the-art using e.g. soft x-ray FEL radiation at FLASH or low intensity pulses provided by the Sub-Picosecond-Pulse-Source at SLAC will be discussed.

The initial layout of the European XFEL foresees the construction of three SASE FEL beamlines. Figure 1 shows a layout of the photon beam distribution with two electron and three photon beam lines. Additional space for two further undulators and photon beamlines is provided. The first six scientific instruments have been determined recently and are listed in Table 1. These instruments will allow covering the most exciting science fields and could be complemented with further instruments in the future.

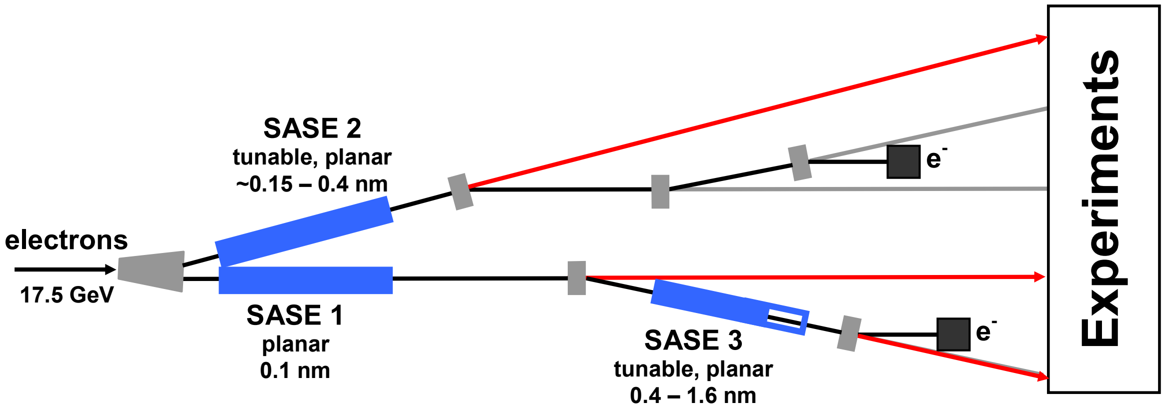

Figure 1. Layout of the European XFEL photon beam distribution. Two electron beam lines serve initially three SASE FEL undulators.

Table 1. Description of the initial scientific instruments of the European XFEL

Name	Description
SPB	**Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters, and Biomolecules –** Structure determination of single particles: atomic clusters, bio-molecules, virus particles, cells.
MID	**Materials Imaging & Dynamics** – Structure determination of nano-devices and dynamics at the nanoscale.
FDE	**Femtosecond Diffraction Experiments –** Time-resolved investigations of the dynamics of solids, liquids, gases.
HED	**High Energy Density Matter –** Investigation of matter under extreme conditions using hard x-ray FEL radiation, *e.g.* probing dense plasmas.
SQS	**Small Quantum Systems –** Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena.
SCS	**Soft x-ray Coherent Scattering** – Structure and dynamics of nano-systems and of non-reproducible biological objects using soft X-rays.

Acknowledgements: The author is indebted to the authors and collaborators of the Technical Design Report for the European XFEL and to the staff at FLASH for excellent experimental conditions. Funding by the European Commission is acknowledged (Grant Pre-XFEL, No. 211604).

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