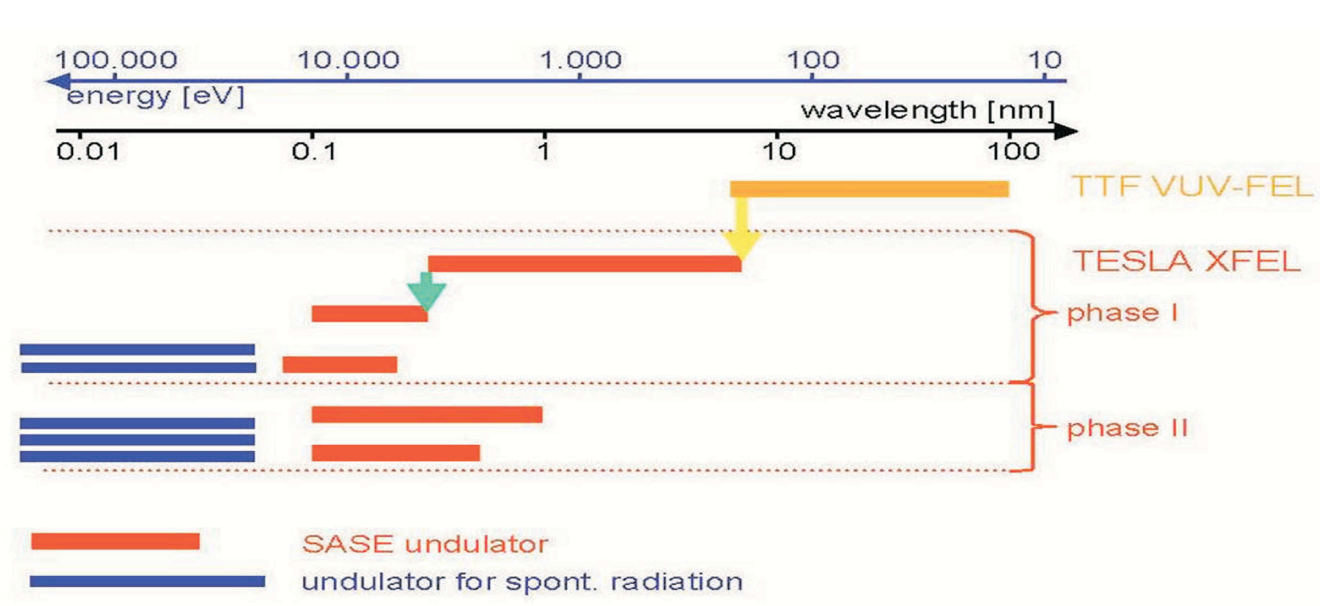
XFEL with TESLA Technology

Layout and Applications of a hard X-Ray FEL

Status and road map towards 0.1 nm wavelength

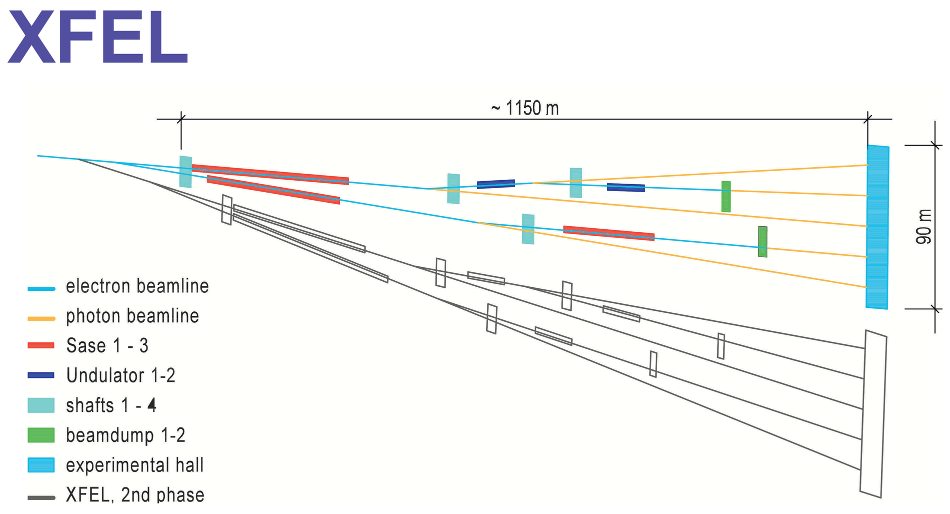
The operation of the Free-Electron Laser (FEL) at the TESLA Test Facility (TTF) until April 2002 has allowed to study for the first time the performance of single-pass free-electron lasers operated in self-amplification of spontaneous emission (SASE) mode in the short-wavelength domain. In summary, we were able to reach saturation for photon wavelengths in the 80-120 nm range, a pulse duration of 50 to 100 fs, peak brilliances up to 2 x 10^{28}, up to 2 x 10^{13} photons per pulse, and a peak power of about 1 GW for a transversely fully coherent beam.
The FEL radiation had been employed in initial exploring experiments aiming to investigate the interaction of highly intense short-wavelength radiation with solids and with cluster and atom beams.
The proposal of a FEL facility for the X-ray domain was prepared and submitted in March 2001. The TESLA XFEL had been originally proposed to be build jointly with the TESLA (TeV-energy superconducting linear accelerator) linear collider. In the process of the evaluation by the German Science council a 2nd design with a dedicated accelerator in its own tunnel and a XFEL laboratory to be completed in two phases was developed. On February 5, 2003 the Federal Ministry of Education and Research decided to realise an XFEL as a European Project.
The next steps towards the short-wavelength FEL will be:

2003	**upgrade of TTF to phase-2 (VUV-FEL for 6-40 nm wavelength)**
2004	**resume of FEL operation at TTF**
>2004	**user experiments at the VUV-FEL at TTF (40 nm > λ > 20 nm)**
2006	**installation of seeding monochromator**
>2006	**user experiments at the VUV-FEL at TTF (40 nm > λ > 6 nm)**
~2011	**start of user operation of the XFEL**



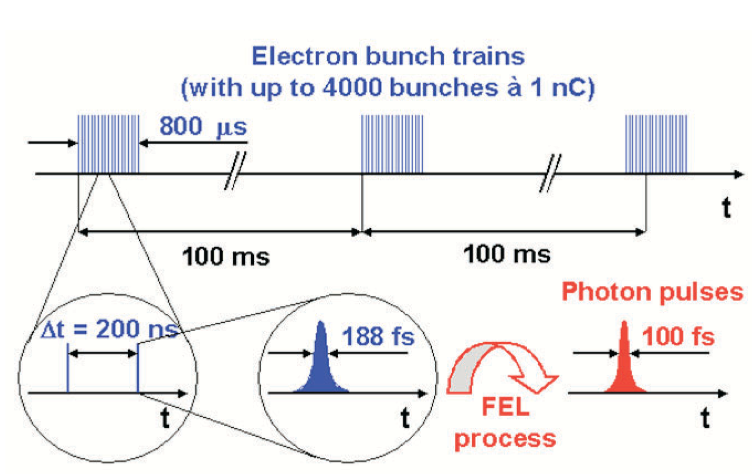
Layout of the TESLA XFEL

- XFEL laboratory for user experiments at 0.1 - 6 nm wavelength
- dedicated 20 GeV electron accelerator in TESLA technology
- Phase-I includes 5 beam lines for 10-15 dedicated experiments
- located in the Hamburg area



Electron beam parameters

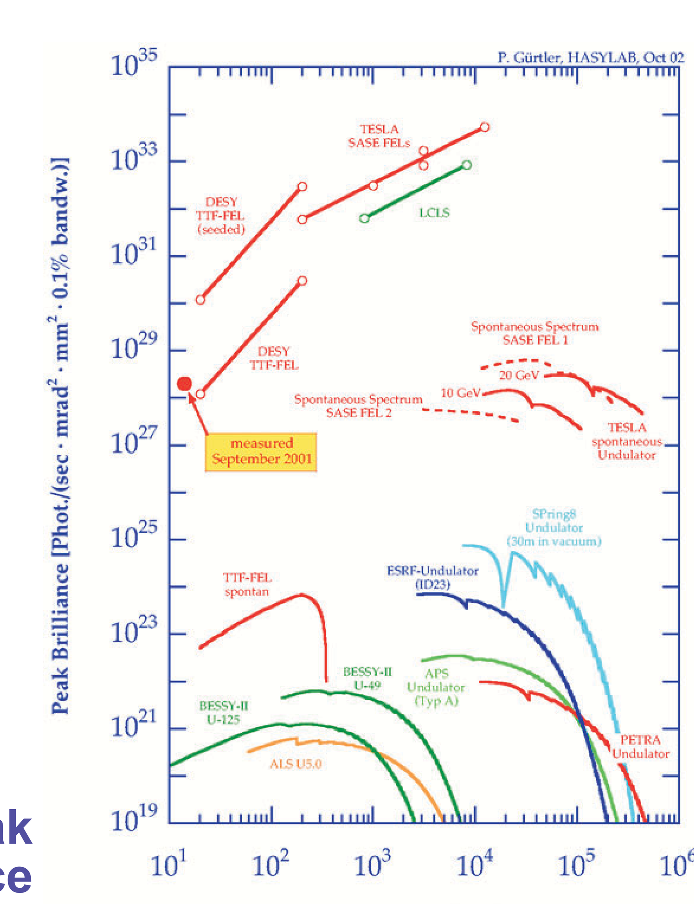
Energy	GeV	10-20
norm.Emittance	π mm mrad	1.4
energy spread	MeV (rms)	2.5
Bunch charge	nC	1
Pulse duration	fs	188
Rep. rate	Hz	10
Bunches	s^{-1}	40.000



Photon beam parameters

Wavelength	nm	1	0.1
Pulse duration	fs	100	100
Peak brilliance		9.3 x 10^{32}	5.4 x 10^{33}
Average brilliance		2.7 x 10^{24}	1.6 x 10^{25}
Photons	$bunch^{-1}$	1.0 x 10^{13}	1.2 x 10^{12}
Peak power	GW	100	24
Spectral bandwidth	%	0.3	0.09

Parameters correspond to TDR, October 2002



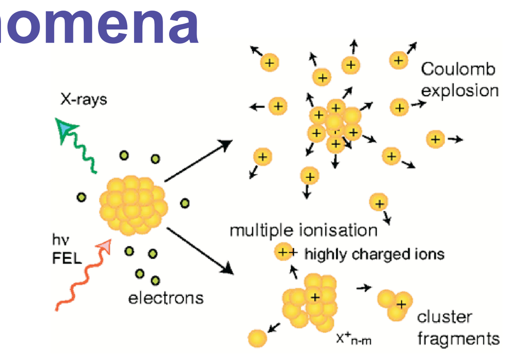
Peak brilliance

Scientific application of XFEL radiation

Atomic, molecular and cluster phenomena
Plasma physics
Condensed matter physics
Surface and interface studies
Materials science
Chemistry
Life sciences
Nonlinear processes and quantum optics

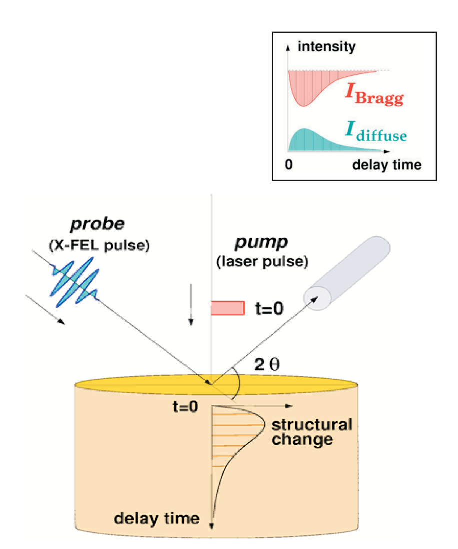
Atomic, Molecular and Cluster Phenomena

Two areas of research are particularly promising: the study of electron dynamics (e.g. multiphoton processes or multiple corehole formation) of atomic, molecular and cluster targets irradiated at different X-ray wavelengths and power densities, and the investigation of the structure and dynamics of molecules and clusters by diffraction of intense femtosecond X-ray pulses.



A schematic of dynamical processes in clusters induced by focused XFEL radiation.

Condensed Matter Physics

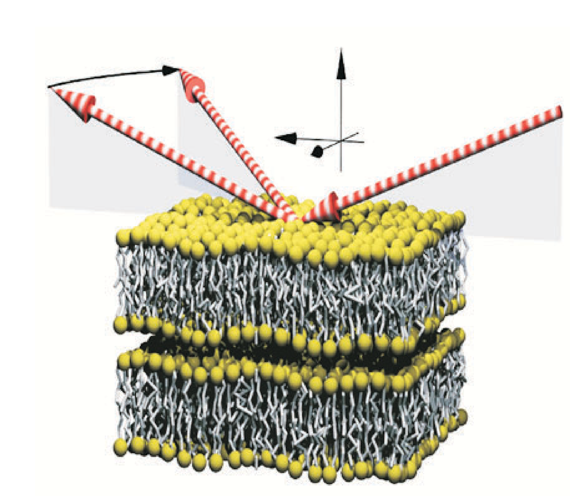


Schematic view of pump-probe experiments

Experimental techniques for the investigation of condensed-matter have reached a very high degree of maturity. These studies are in general restricted to the ground-state properties of the system. The investigation of dynamic processes is in its infancy and the present-day X-ray sources cannot provide adequate means to investigate them at sufficient detail to advance our understanding of complex processes. The use of coherent X-ray radiation from the XFEL provides the possibility to access dynamic properties of disordered systems, both in bulk and at surface. The study of ultrafast processes using X-ray FEL radiation, e.g. investigations of magnetization phenomena or phase transitions, will provide new insight into processes of fundamental scientific interest and high technological importance.

Surface and Interface Studies

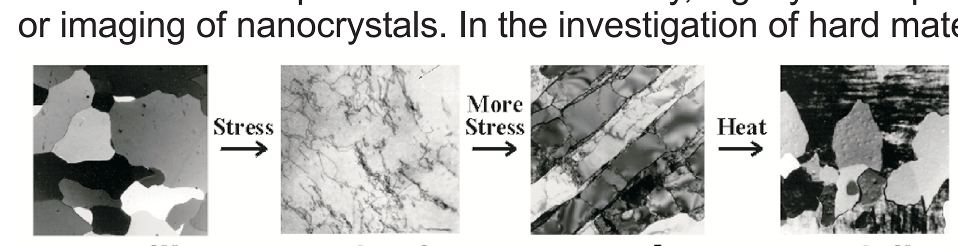
The investigation of ultrafast processes at surfaces, like chemical reactions, demands the study of transient states during such reactions, of their decay constants and related structural properties. Focussing to dimensions smaller than ~100 nm will open new opportunities for studying matter with inhomogeneous distribution of properties. The detailed understanding of dynamic properties of surfaces, interfaces and aggregates will be of crucial importance. Investigation of technologically important processes, such as friction, will benefit greatly from the application of coherent X-ray scattering.



Sketch of a surface scattering and diffraction experiment from a disordered biomembrane layer stack.

Materials Science

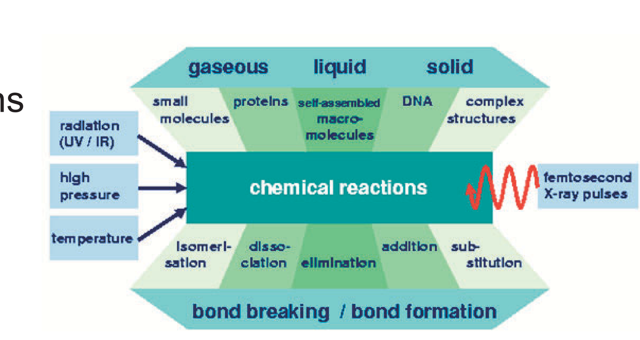
X-ray FEL radiation will enable the investigation of polymer processes, such as phase formation, reorientation, crystallization, nucleation, or diffusion. It will be possible to collect information from nanomaterial samples not accessible today, e.g. by nanospectroscopy, diffraction from nanocrystals or imaging of nanocrystals. In the investigation of hard materials, ultrashort X-ray pulses (around 100 keV) will enable to investigate structural and dynamical properties of metals, alloys, ceramics, as well as real-time studies of ready-made workpieces under varying external parameters.



Typical metal structures seen in traditional microscopes.

Chemistry

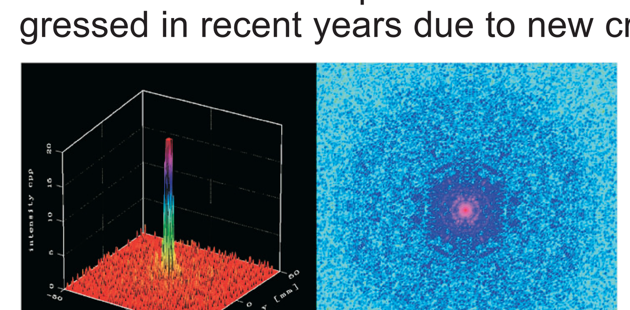
In chemistry the possibility of time-resolved investigations of ultrafast processes, such as chemical reactions or conformational changes is of utmost importance. The complexity of chemical reactions in general, and the involved ultrashort time-scales require the properties of intermediate states to be determined at time scales of the order of 100 fs. X-rays have the particular advantage to obtain 3D structural properties with atomic resolution in a direct way that cannot be observed otherwise. Applications of these techniques extend from solid-state chemistry through catalyst research to technological applications, e.g. for the development of optical switches.



Applications for time-resolved investigation of chemical reactions.

Life Science

In life sciences the quest for structural investigation of macromolecular assemblies has progressed in recent years due to new crystallization techniques for large molecules. Overcoming the limitations of crystallization XFEL radiation enables the investigation of large molecules, single-particles, clusters of a few molecules, or nanocrystals taking limitations due to pulse duration, focal spot size, and radiation damage into account. The coherence further enables imaging of entire cells under ambient conditions and yields high-res. spatial information.



Diffracted intensity of a single blue tongue virus capsid from a single ≈ 3 x 10^{10} photon pulse focused into 0.1 µm