SASE X-Ray Free Electron Laser in DESY
--The 4th Generation Light Source

Wenlong SHI
Deutsches Elektronen-Synchrotron DESY
22603 Hamburg, Germany

ABSTRACT
The SASE - Free Electron Laser, the new light source constructed at DESY in Hamburg will sharpen the sight of 21st century scientists to an extent that has never been reached before. they allow contrasty pictures of atomic structures to be taken in a way which is not possible today. A laser for X-ray radiation will open up new insights into the depths of living cells, molecules, and materials. It is an ultra-brilliant X-regime light (**XFEL**), a 300 meter long Free Electron Laser without mirrors and laser seed, the world-wide first and only X-ray laser of this kind.

1. Introduction

Over the past thirty years beyond the narrow optical spectral window up to the hundred keV regime synchrotron radiation has provided an increase in flux and brightness by more than 10 orders of magnitude (show in Fig 1). The development of storage ring designs with special magnetic components, called wiggler and undulator, has led to 3rd generation machines specially designed for synchrotron radiation research, which are surpassing by far their design goals. This illustrates impressively how predictable accelerator physics has become today. But unfortunately the current synchrotron radiation sources are still too “dim” at Angstrom wavelength regime (X-ray), though the spectrum is quite broad.

Because of the performance of low emission e of electron guns and operation of very precise undulators, most recent successes in accelerator development concerning linear accelerators have opened the route to a new jump in photon source quality. X-ray lasers coupled to linear accelerators can possibly produce coherent X-rays with true laser properties through very long undulators. Such a source of coherent laser-like X-rays would have many applications and the search for such a device has occupied many scientists. To be an efficient research tool, it would have to provide stable intensities with short pulses and repetition frequencies similar to what is found in optical lasers. Exactly this seems to be possible by using the so-called self amplified spontaneous emission process **SASE**.

The XFEL will be a unique light source in the X-ray regime. It is 6 orders higher of magnitude of the average brilliance and 10 orders higher of magnitude of the peak brilliance than that of 3rd generation light sources, as the ESRF, APS, SPRING8 and so on.

Wavelength, brilliance, coherence, and timing down to the fs regime are the properties of light, which has the highest potential for new science done with a XFEL. The uses of linear and circular polarization as well as wavelength tunable ness are clearly additional attractive characteristics of this source as it’s the continuous spontaneous background.

Till now several scientific and technical workshops were therefore run over the past five years to assure the technical feasibility and to reveal in detail the new scientific possibilities of such a photon source. The proposed linac based XFEL should provide X-rays at wavelength down to 1 Angstrom in pulses of 100 fs length with intervals between pulses ranging from ns to ten ms. This source is fundamentally come from an undulator in that the emitted radiation causes electron density modulation at the optical wavelength within each electron bunch and leads to true stimulated emission and full transverse coherence.

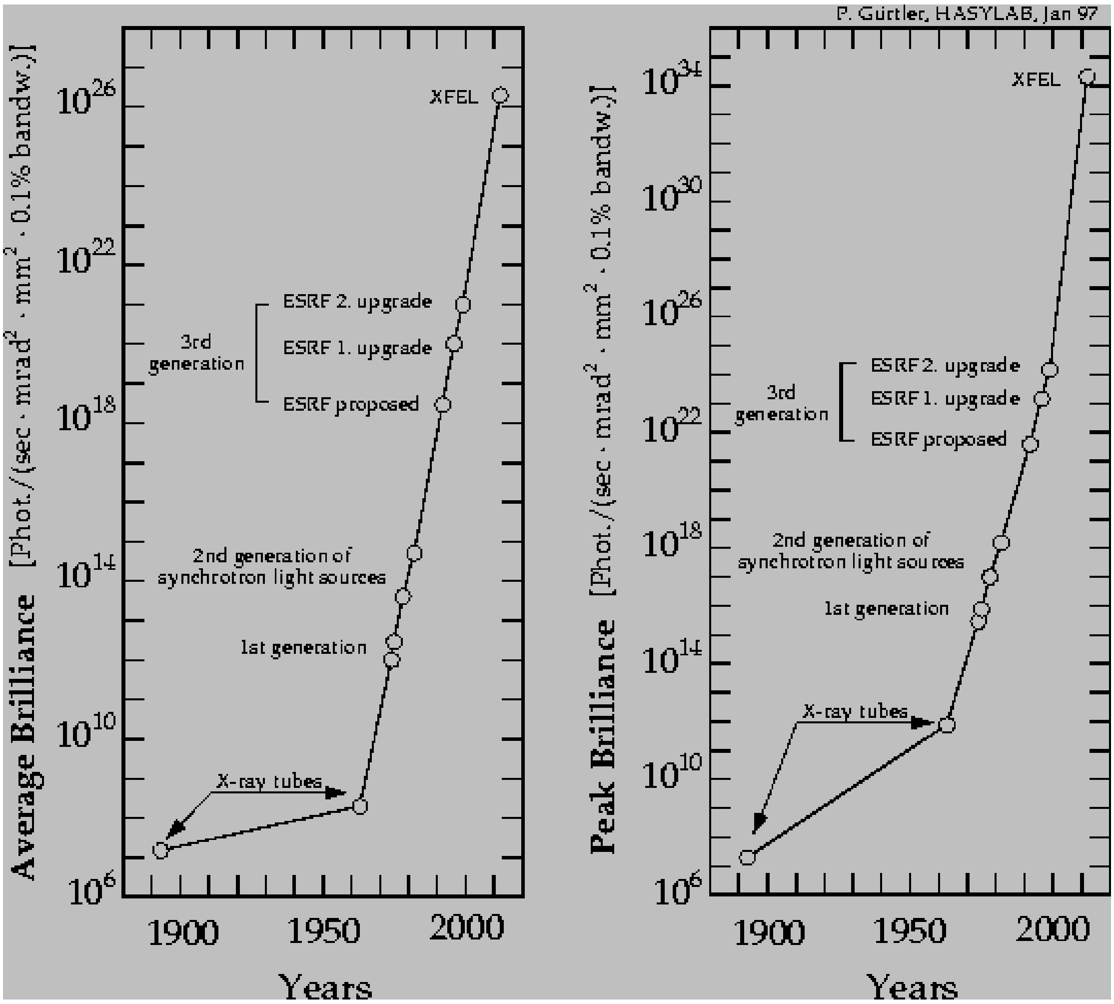


Figure 1: Brightness development of X-ray sources since the discovery of X-rays by W. C. Rö ntgen in Wü rzburg, 1895

2. Characters and Applications of FEL

The XFEL has attractive properties:

- Very high brilliance (10^{34} Photons/sec*mrad^2*mm^2*0.1bandwidth)
  Peak power is 10 thousand million times higher than the most modern x-ray sources
- Spatail and partial coherence
- Short puls e (100 fs)

adding:

- Tunable wavelangth
- Linear and circular polarization

In preparation of the scientific case for the TTF FEL proposed by DESY a first meeting with potential user took place at DESY in Nov. 1994. Since then working group for the following fields of application have been formed:

- Microscopy
- Atoms, molecules, ions and plasmas
- Clusters and radicals
- Reaction and relaxation dynamics in photo-chemistry and surface science

- High resolution photoelectron spectroscope of solids
- Magnetic materials, dichroism

On science research we have some topics following for applications concerning in:
The scientific case has been discussed on two meetings on Nov. 1994 and Apr. 1995.

* Diffraction
  - Magnetism
  - Surface and Interface Science
  - High Pressure Work
  - Material Science
  - Soft Matter
  - Biology

* Nuclear Resonant Scattering
  - Expected Impact
  - Biology
  - Nuclear Physics

* Spectroscopy
  - X-ray Absorption Spectroscopy
  - X-ray Standing Waves
    - Surface Studies.
    - Extremely Dilute Systems.
  - Atomic Physics

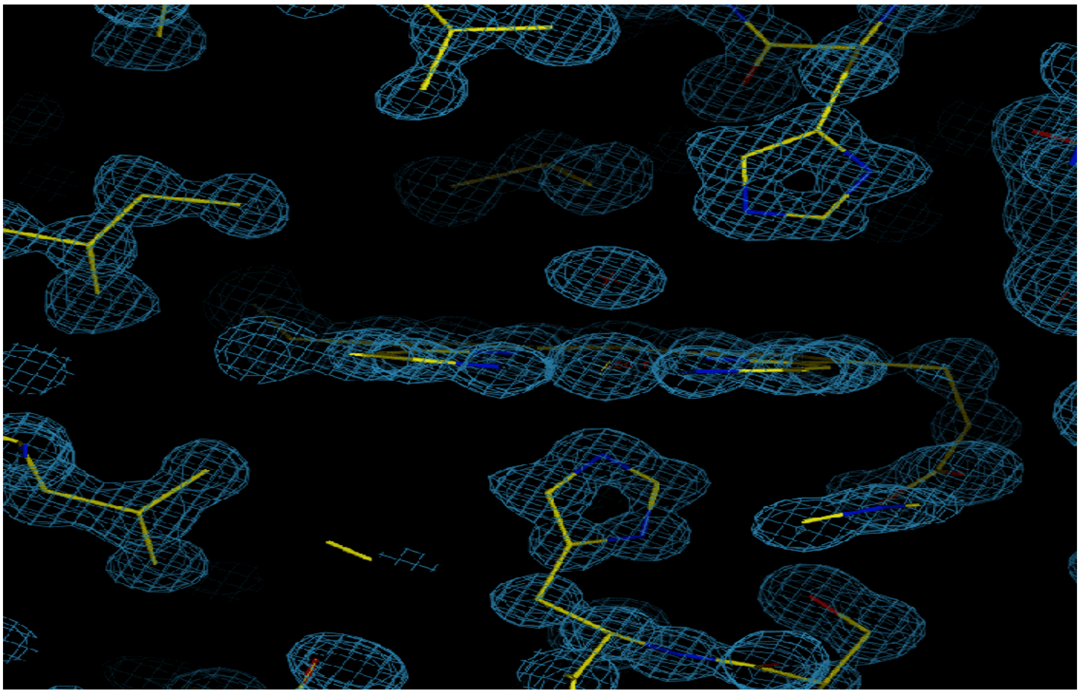
* Scattering
  - Inelastic Scattering from Surfaces, Interfaces and Thin Films
    - Phonons in Thin Films
    - Surface Melting
    - Surface Layering in Liquid Metals: Phonon Spectrum
    - Surface-related Inelastic Precursor of Structural Phase Transitions
  - X-ray Scattering from Laser-induced Charge Densities
  - Inelastic X-ray Scattering Spectroscopy

* Spectroscopy with Coherent X-Rays
  - Status and Applications
    - Dynamics of Disordered Systems
    - Dynamic Structure Factor of Liquids
    - Crystal growth and surfaces
    - Rapid Solidification
    - Structural Studies of Disordered Biological Systems
  - Expected Impact

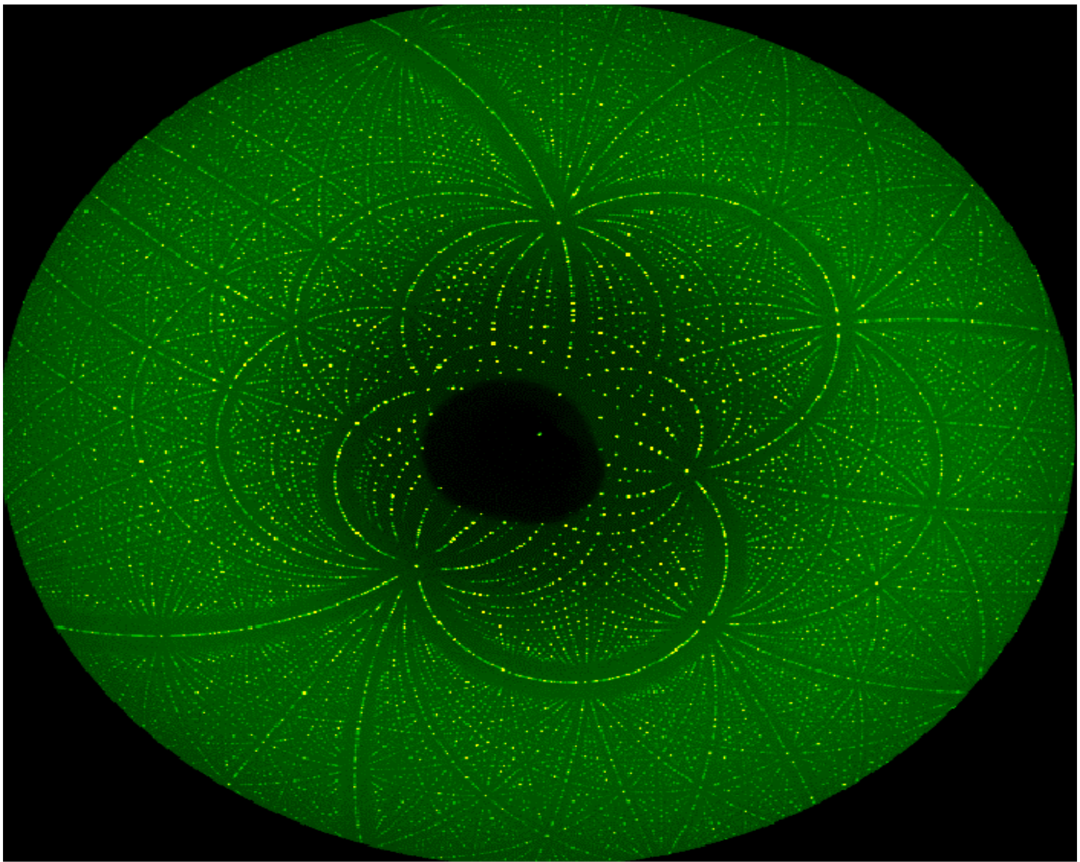
* Microscopy and Imaging with Coherent X-rays
  - New Possibilities in Imaging
  - Phase Contrast Imaging and Tomography
  - X-ray Topography
  - Holography
  - Microscopy

- Quantum Optics
  - Examples of Applications
    - Precise Frequency Shifts of X-rays
    - Spontaneous Parametric Conversion of X-ray Photons, Bell's Inequality, Two-photon Interference
    - Spectroscopy on Muonic Hydrogen
    - Nonclassical States of Light
    - Atom Beam Interferometry

Here have two samples to show:



Laue diffraction pattern is from cubic 2Mn-catalase (Bourenkov, Barynin, Bartunik). The XFEL will permit to record such exposure within 100 fs for time-resolved investigations of rapid conformational transitions.



Structural model of myoglobin at 0.85 Å resolution (Popov, Kachalova, Bartunik). The atomic resolution shows features corresponding to the scattering power of a single electron. The XFEL permits 100 fs time resolved studies of rapid conformational transitions at atomic resolution.

3. Principle of SASE-XFEL

When an electron bunch flights with light speed and changes direction under magnetic field on a storage ring, it will emit photons in direction of tangent on its curve. These photons were called synchrotron radiation. What happens if an electron flights through an undulator, which exists fields of opposite polarity alternately? (As in Fig 2) It emits a radiation field. Suppose N electrons are concentrated in one bunch. The power of radiation is not N times as from an electron, but N^2 times big as it. Each electron is stimulated through electromagnetic field emitted by another electrons to intensify his radiation. Man named it also as " Stimulated Emission" . Meantime, the electrons in bunch were ordered in space-regular, which corresponds certain wavelength.

In order better to understand this principle, we observe one single electron, which as is stringed in a string of pearls, moves through a special magnet we called undulator. With the electron passing through magnetic centrifugal-route it brings into the electron making a wiggly flight by left and right. Aroused by wiggly moving, the electron radiates electromagnetic wave of determined wavelength and all are with flighting direction.

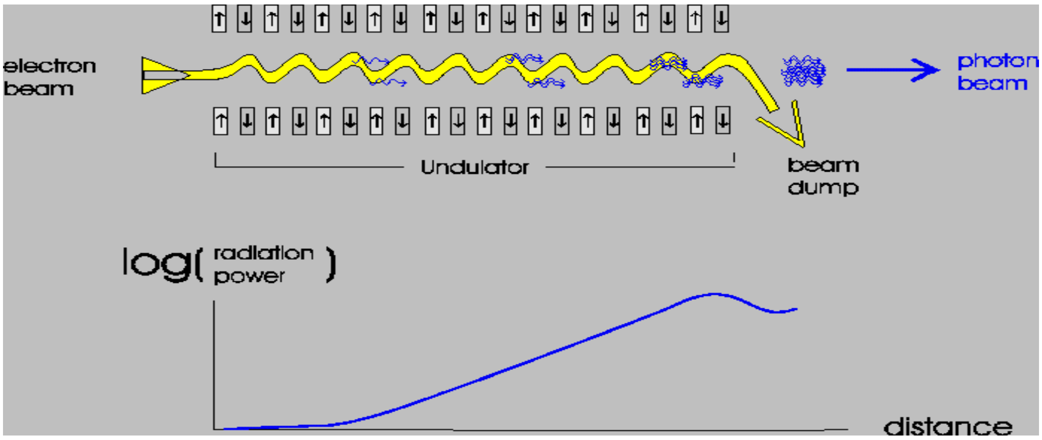


Figure 2: Schematic Diagram of a Single-Pass Free Electron Laser (FEL) operating in the Self-Amplified-Spontaneous-Emission (SASE) mode.

How determine the wavelength? The light spreads with its speed $c=3x10^8$ meter per second and electron must be in any case slower than light acording particle relative-theory, determining λ_u out the route of undulator, the electron falls behind half step opposide the light-speed per coverd undulator-periode. After each magnetic field period the electron motion-state is total changed, when his kinetic energy E much bigger than so called static-energy $E_0= m_0*c^2$. In our case, m_0 is the electron mass, E_0=0.511Mev, simply writing $\gamma = E/E_0$, the difference of both speeds can express: $c-v = c/2\gamma^2$, it is very small when the kinetic energy is so big (means big γ). Then the radiated wavelength can be culculated directly from the difference of speeds, thinking of the wiggly movement of electron in undulator, it's flight speed is not so fast as expect, the formule runs:

$$\lambda_{em} = \lambda_u/2*\gamma^2(1+K^2/2)$$

The undulator-parameter can be wrote $K=e*B_u*\lambda_u/2\pi*m*c$ ($=0.934*B_u*\lambda_u$), here B_u is it's magnetfiel with unit Tesle, λ_u is the magnetic wavelength with cm. B_u and λ_u must be expect that K approximately is 1. Electron with for example E=500MeV (that means γ =1000) radiates light λ_{em} which 1 million times is smaller than the period of the undulator.

Now we look at again Fig.2a and see how does the electron interfere with the producted electromagnetic wave on running time position? We larged the picture for better obsurving and separate the wave from electrons movement, in fact they are overlapping for each other. The wave exsists an electric field, as the arrows hinds, it's direction changed periodicaly. As we know the λ_{em} much smaller than λ_u of undulator. We can also see that the wave spreads quicker than the electrons. Here we mark thick arrows at same position on waveforms for each period λ_u.

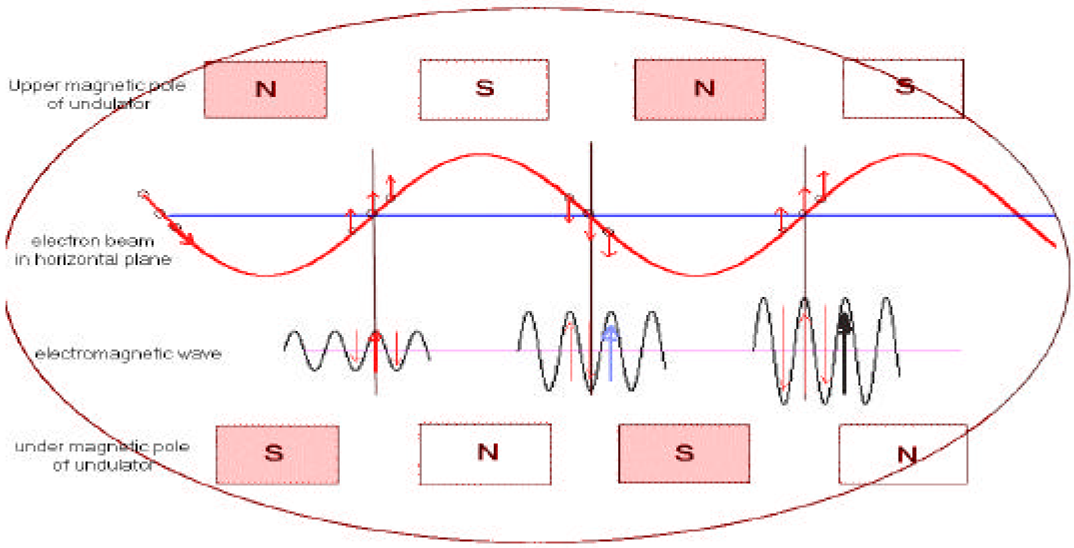
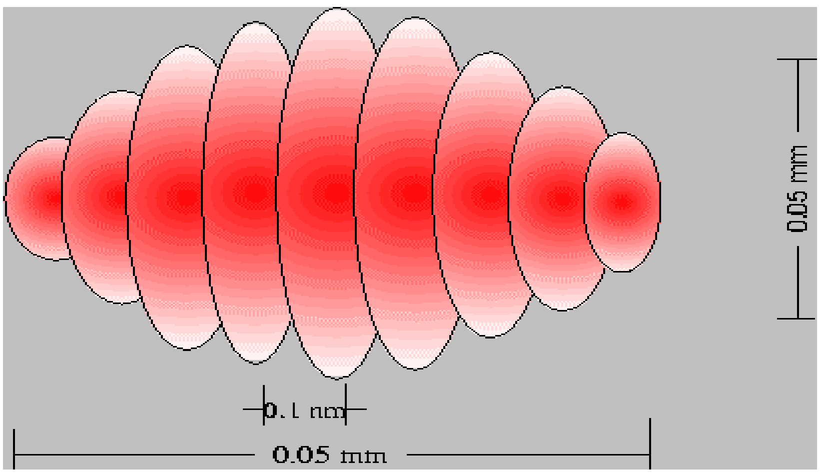


Fig. 2a Enlergement in undulator.
In order to understander SASE free electron laser fundamental, we observe an electron beam through the undulator

When the movement of electron is same direction as the field, the electric field will be amplified and the electrons will brake down, while opposite case the field will be weak-minded and the electrons will accelerate. As we know, in fact we find there interference each other, it dependent sensitivity upon the position of the electrons: the middle arrow of tree moves same direction as field, but the arrow of neighbor, from only half wavelength $_{em}$, moves against the field. As following the field is amplified and the middle of electron would be slower, the field is reduced and the neighbor electron little more quickly, it built out a longitudinal density-modulation in electron bunch. (Show in under of Fig. 3) This function is very remarkable and only the electrons is at the position out of per undulator period l_{u}, that means though differentiated equation of wavelangth above, because this point the electron movement direction is same as l_{em}.



Fgure 3: Schematic Diagram of the micro-bunching of the X-ray FEL electron beam engraved density-modulation. Note that in reality the nuber of slices is much larger.

As mentioned, the stimulated emission, which corresponds certain wavelength, happens when the electrons arranged with space-regulation in a bunch. We can hold on, at the beginning, a bunch of disordered electrons interacts with radiation field, which produced by himself in the undulator, leading to its engraved density-modulation and for this reason stimulates strongly this wavelength's radiation again. This stimulation is so effective, more stronger the electromagnetic field is and more the wave is increased as avalanche, until saturation. Man calls it Self Amplification Spontaneous Emission. This principle was first time discussed by A.M. Kondratenko and E.L. Saldin in 1980, worked out in detail by R.Bonifacio, C. pellegrini and there colleague by 1984. At end of undulator the power of the radiation is several orders higher than normal undulator. By changing the electron beam energy the wavelength λ_{em} can continually be changed in broad regime. The radiation is coherence and producted by stimulating emission of free electron, we called it as " Free Electron Laser" .

4. SASE-XFEL in DESY

In the frame of international collaboration, DESY is now pushing to constructing an XFEL test facility in parallel with the TESLA test facility (TTF).

*** TTF FEL Phases:**
According MeV to the present schedule, The phase 1 of the TTF FEL project which has been approved, is to reach a 42 nm laser with a 390 MeV beam through a 15 meter length undulator. In the phase 2 we'll extend the beam energy to 1 GeV, getting 6 nm laser using 30 meters undulator. A 100 meters long undulator is foreseen for the XFEL at 1 angstrom.

*** Telegram:**
It is a pleasure to inform you that in Feb. 22. of this year we succeeded to observe first lasing of the TTF FEL. The observed **wave length is 109 nm**. The increase in intensity compared to the spontaneous radiation is more than 2 orders of magnitude. The width of the radiation cone is 300 microradian as compared to 3 milliradian for the spontaneous radiation. The intensity of the radiation shows a strong dependency on the bunch charge. All observations are in agreement with what is expected for SASE. We are looking forward to the coming experimental programme.

*** Outline:**

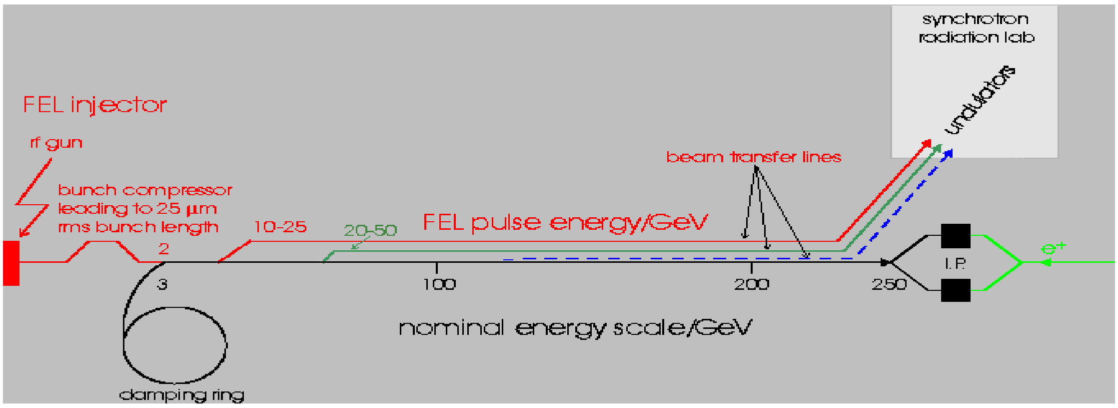


Figure layout: Sketch of a coherent X-ray source laboratory based on a linear collider installation. The beam can be extracted at any energy between 2 and 250 GeV and is transferred inside the linac tunnel to the X-ray lab located close to the interaction points (I.P.). Multiple extraction lines could be utilized in parallel, so that various beam energies are available in the X-ray lab quasi-simultaneously. The beam of XFEL electron is provided by an RF gun and followed by a sequence of bunch compressors.

*** Electron Beam Parameters**:
In order to get such wavelength FEL, the transverse coherence condition imposes a tight requirement on the transverse emittance ε_t of the electron beam:

$$\varepsilon_t = \varepsilon_t^n / \gamma \leq \frac{\lambda}{4\pi}$$

For λ_{em} =6 nm, γ =2000, this requires $\varepsilon_t^n < 1\ \pi$ mrad-mm. The saturation length significantly increase if ε_t^n is large. A beam with smaller horizontal emittance and much smaller longitudinal emittance is required, which can be provided by an RF photo-cathode gun.

With the present stage of technology of RF guns, an XFEL could be made operating in the several Angstrom range. Anticipating improvements in gun performance by about a factor of 5, a normalized emittance of less than 1π mrad-mm (for 1 nC bunch charge) and a longitudinal emittance of 20 keV mm.

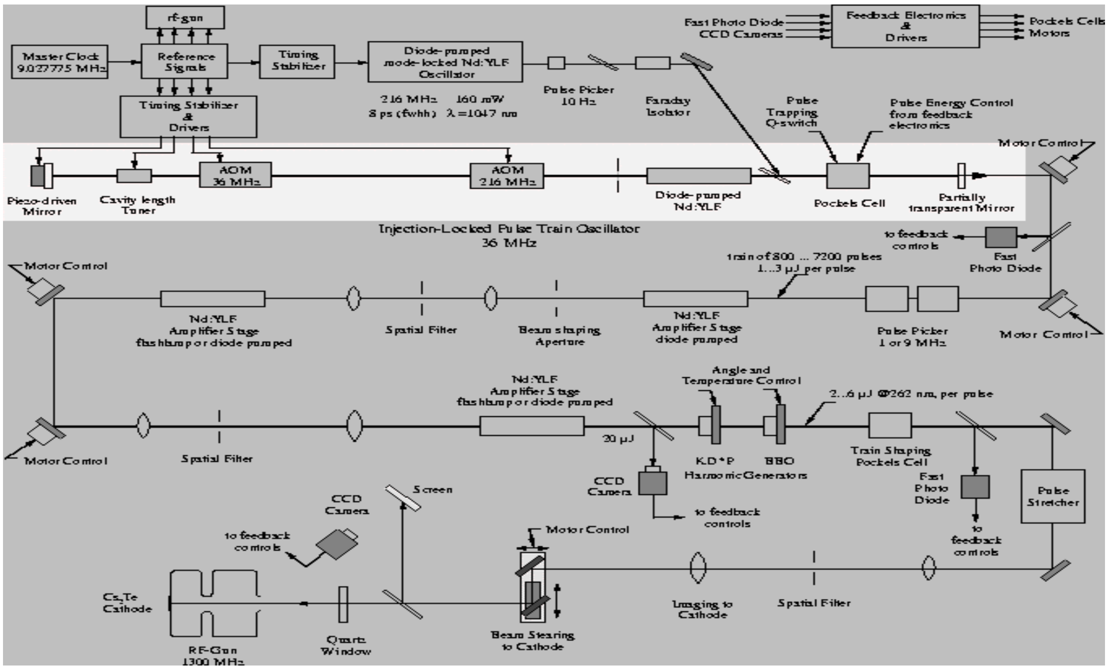


Figure laser injector: Bloc diagram of the laser driving the RF gun of the TTF FEL.

*** The RF electron gun:**
The electrons are photo-emitted from a cathode, which is placed in the split plane in RF gun. The electron start with nearly zero velocity, some phase slippage occurs respect to the RF wave. When it's energy less than 20MeV in a L-bang gun, the electron space charge induced emittance e_t becomming bigger. Carlsten's emittance compensation technique can improve this emittance. From Figure of phase, after drifting behind lens in phase-space showing emittance reduction due to different velocities of rotation of the beam center and the tails.

In Berlin Max-Born-Institute (MBI), they have a proposal of this laser system for emission of photo with DESY's cooperation. The time structure of micro pulses and the mean power requirement are given.a Cs_2Te-cathode has to be illuminated by UV light (l < 275 nm) in order to achieve reasonable electron extraction efficiency.

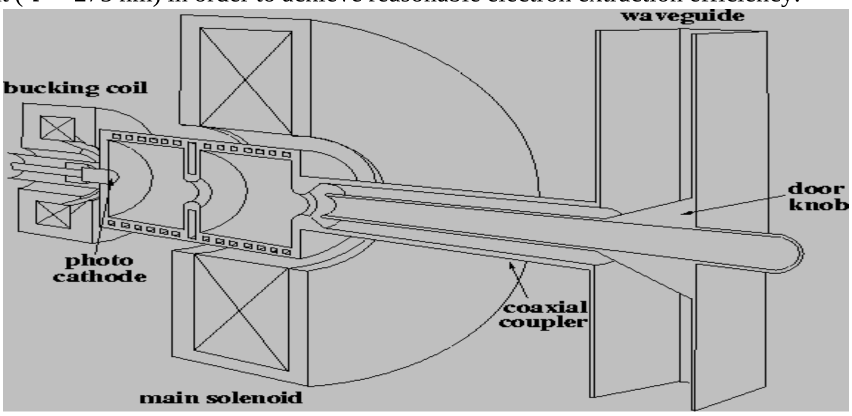


Figure RF gun: Cross sectional view of the RF gun (schematic) with the gun cavity, the cathode plug, the main solenoid and the bucking coil and the coaxial input coupler. The RF is coupled from the rectangular wave-guide via a knob of door transition into the coaxial line and the cavity. The electrons leave the gun through the inner conductor.

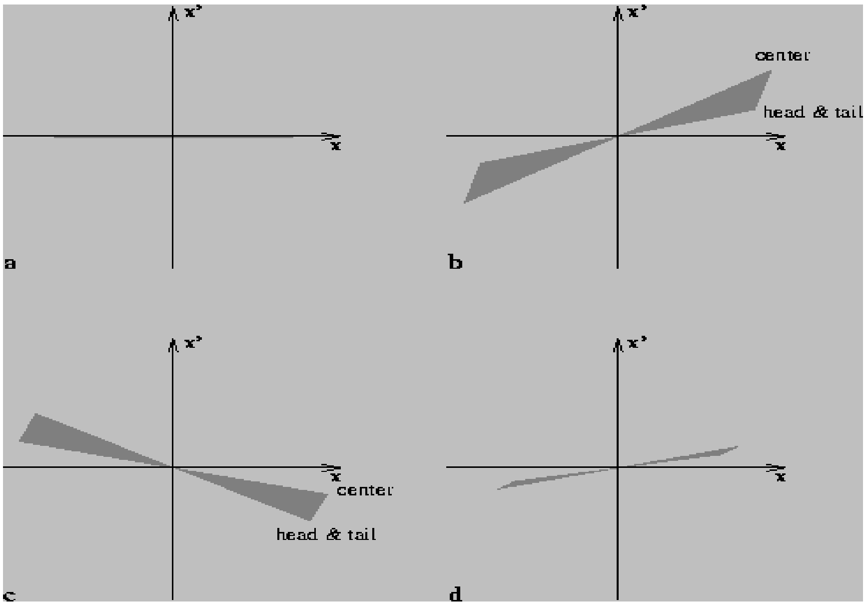


Figure Carlsten's emittance compensation of space charge force: Transverse phase space plots showing schematically transverse emittance growth and reduction due to space charge forces. (a) Initial phase space with small (zero) emittance at the gun. (b) Phase space after transport up to the lens, showing the increase of the projected emittance due to the different focusing strength at the bunch center and the tails. (c) An external focusing kick has rotated the phase space distribution. (d) Phase space after a drift behind the lens. The projected emittance is decreased due to the action of the space charge forces.

*** Longitudinal bunch compression:**

Within a certain undulator length, a very high instantaneous beam current is needed to reaching phonon power saturation in the undulator. For our FEL, it is 2500A, corresponding to 50 μm rms bunch length for a 1 nC bunch charge. This value is not attainable directlt from the electron gun, because the electron space charge force would blow up both transverse beam size and the momentum spread. So, the bunch compression is foreseen to reducing thr ems bunch length from 2 mm down to 50 μm in three steps.

By passing a high gradient RF structure at zero-crossing phase, a linear correlation between energy and longitudinal position is induced in bunch. Then follows a sequence of bending magnets where particles with different energies have different path lengths, because they travel on different radial circles through the bending magnets with dispersion. Therefore an ideal full compression can be achieved with the right choice of parameters. (As Figure compressor showing)

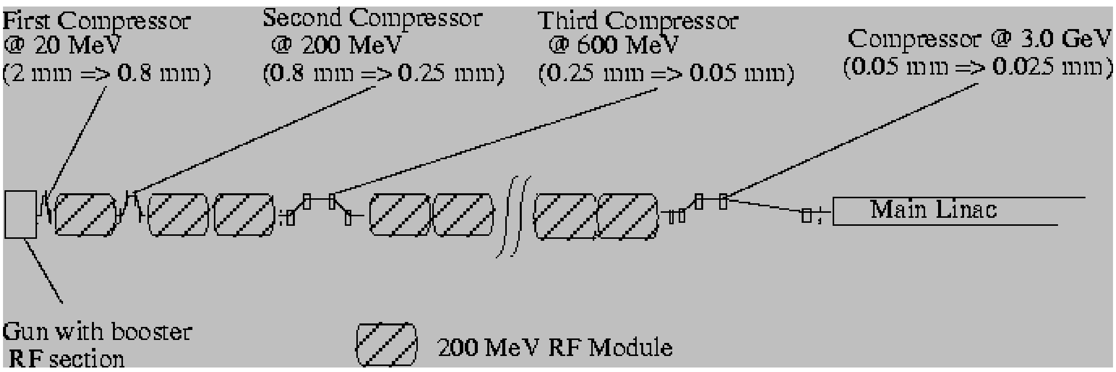
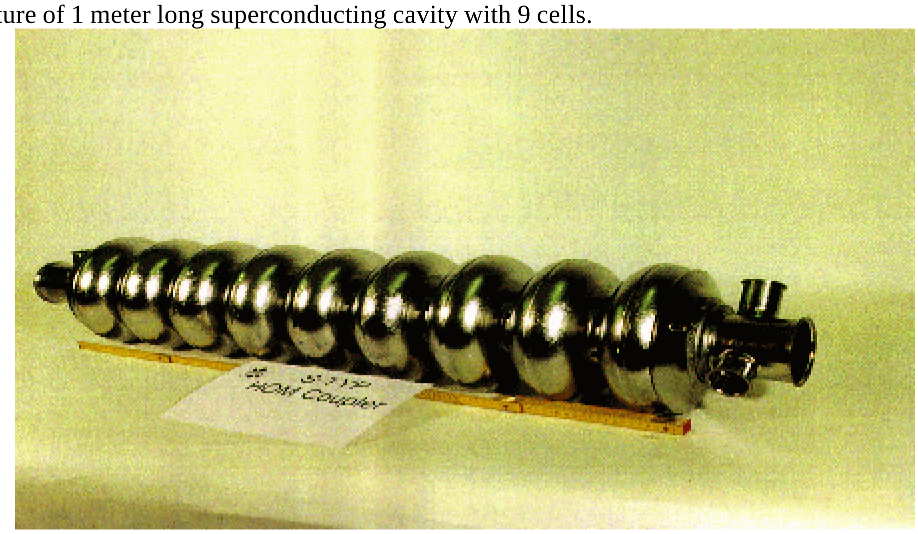


Figure compressor: Schematic layout of injection linac and bunch compression system

We can consider performing the bunch compression in one step at an energy level, where space charge is not critical any more (When >300MeV). However, even at the comparatively low TTF rf frequency, the cosine-like time dependence of the accelerating field would then impose an intolerable nonlinear correlated energy contribution along the bunch. The proposed solution is to perform compression is three steps at 22 MeV (2 mm → 0.8 mm), 140 MeV (0.8 mm → 0.25 mm) and 390 MeV (0.25 mm → 0.05 mm).

*** Acceleration:**
At the first phase, there are three TESLA cryo-modules for accelerating the electron beam. Each kryo-module consist of eight superconducting 9-sells -cavities in super-fluid He bath (2K). A total of 390 MeV energy gain of electron is expected with 15 MV/m nominal operating gradient. Due to the low frequency (1.3GHz), the big geometry, the electron wakes are considerable small. If σ_s = 1mm, the langitudinal wake $W_{||}$ is only 17.8 V/pc in 9-cell superconducting cavity. The HOM power level is also low for most HOMs. In phase 2, accelerarating gradient of 25 MV/m is necessery and adding four kryo-modules for getting 1 GeV energy.

Here show the picture of 1 meter long superconducting cavity with 9 cells.



*** Undulator**:
The undulator is the most prominent FEL critical component. A planar hybrid undulator is choice with period length λ_u = 27 mm and peak magnetic field B_u = 0.5Twith 12 mm gap. The main challenges are the total length of 30 m. In order to easy manufacturing so long undulator and greater flexibility, it will be subdivided into 6 modules of 4.5 m length adding 6 matching sections of 0.5 m between the modules. In matching sections beam-monitors, beam-steering elements, collimators and phase shifters will be placed. The additional quadrupole focusing and defocusing to be supplied with 0.66m distances for each other to keep the beam-size smaller over the whole length of undulator and tight tolerance. Two types error can destroy the lasing process. The transverse beam deviation comes from electromagnetic interaction with beam bunch; the other is the longitudinal phase shake. A tolerance of 10 μm is necessary over one undulatot length of 4.5 meters for keeping reduction of gain less than 15%. That means an integrated field error of 15 Tmm^2 at 300 MeV.

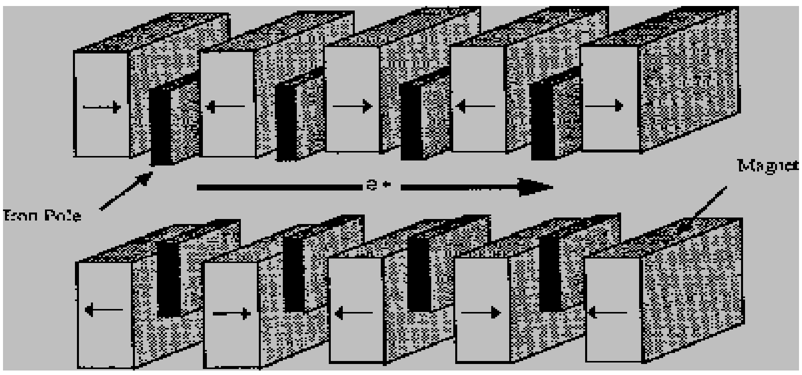


Figure Undulator: Schematic of a Hybrid Undulator consisting of magnets (light gray) and soft iron pole pieces (black).

*** Process:**

We have several computer codes available to simulating XFEL process, E.g. NUTMAG, S2R, TDA, GINGER for investigating the start-up respectively from noise, the lethargy, exponential and saturatuin regimes. They were written by different group and based on different approaches. But by all of the fact there is no essential disagreement. Derived from one dimension Lorentz-Maxwell equations nm, we can get the so-called parameter r as the FEL energy conversion efficiency.

From Fig. Undulator, we can see the SASE-laser has a strong stochastic behavior both in the temporal and spatial domain, because it is starting from random micro-bunching by just-in phase spontaneous radiation. One expects large fluctuations of the instantaneous radiation power distribution inside each radiation pulse, changing from pulse to pulse, but the radiated power averaged over each pulse will be quite stable.

*** DESY - EXPO 2000: Light for the new Millennium**

A 300 meter long superconducting X-Ray laser microscope will be exhibited at the Research Center DESY for Worldwide Project **EXPOSITION** 2000 from 1. Juni - 31. October. Openig time is daily 10 a.m. to 7 p.m. with admission free.
Tel: 0049-40-89981919

* Design parameters of the TTF-FEL (VUV) and the X-ray FEL (TESLA)

	TTF-FEL Phase I	TTF-FEL Phase II	X-ray FEL
Electron energy (GeV):	0.39	1.0	25
Normalized electron beam emittance (π mm mrad):	2	2	1
Electron beam emittance (π nm rad):	2.6	1.0	0.02
Electron bunch charge (nC):	1	1	1
RMS Electron bunch length (µm):	240	48	24
RMS Electron bunch width (µm):	68	55	18
Bunches per second:	72000	72000	56575
Photon energy (eV):	29.37	192.8	12311
Photon wavelength (nm):	42.22	6.4	0.1
Peak photon beam saturation power (GW):	0.5	2.3	65
Photons per bunch:	2.1 E14	3.9 E13	6.6 E12
Peak photon beam flux (photons/sec):	1.0 E26	1.0 E26	3.3 E25
Peak photon brilliance (photons/ sec/ mm^2/ $mrad^2$/ 0.1%):	4.3 E28	2.2 E30	9.7 E33
RMS Photon beam spectral bandwidth (%):	0.28	0.2	0.07

5. References

1) J.M.J. Madey, Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field, J. Appl. Phys. 42. 1906, 1971

2) A. M. Kondratenko, E. L. Saldin, Generation of Coherent Radiation by a Relativistic Electron Beam in an Ondulator, Part. Accelerators, 10, 207, 1980.

3) R. Bonifacio, C. Pellegrini, L.M. Narducci, Collective Instabilities and High-Gain Regime in a Free Electron Laser, Opt. Cummun. 50, No. 6, 373, 1984.

4) R. Brinkmann, et al., An X-Ray FEL Laboratory as Part of a Linear Collider Design, Proc. 1996 FEL Conf., to be Published in Nucl. Instr. Meth. A , 1997.

5) G. A. Loew (ed.), International Linear Collider Technical Review Committee Report, SLAC-R-95-471, 1995.

6) T. berg, et al., A VUV Free-Electron Laser at the TESLA Test Facility at DESY, Conceptual Design Report, DESY Print TESLA -FEL 95-03, 1995.

7) J. E. Clendenin, RF Photoinjectors , to be published in Proc. Linac Conf. Geneva , 1996.

8) C. Hovater, et al., The CEBAF RF separator system, Proc. 1996 Intl. Linac Conf., Geneva, 1996.

9) Ya. S. Derbenev, et al., Microbunch Radiative Tail-Head Interaction, DESY Print TESLA -FEL 95-05, 1995.

10) E. L. Saldin, E. A. Schneidmiller, M. V. Yurkov, On the Coherent Radiation of an Electron Bunch Moving in an Arc of a Circle, DESY Print TESLA -FEL 96-14, 1996.

11) M. Dohlus, T. Limberg, Emittance Growth in Bunch Compressors,Proc. 1996 FEL Conf., to be Published in Nucl. Instr. Meth. A , 1997.

12) R. Tatchyn, et al. , Proc. PAC93, Washington, 1993.

13) J. Pflü ger, et al., The Undulator for the VUV-FEL at the TESLA Test Facility, Proc. 1996 FEL Conf., to be Published in Nucl. Instr. Meth. A , 1997.

14) R. Bonifacio, et al., Spectrum, Temporal Structure, and Fluctuations in a High-Gain Free-Electron Laser Starting from Noise, Phys. Rev. Lett. 7370, 1994.

15) L. R. Elias, Proc. 1996 FEL Conf., to be Published in Nucl. Instr. Meth. A , 1997.

16 J. Rossbach, et al. Interdependence of Parameters of an X-Ray FEL, Nucl. Instr. Meth. A 374 401, 1996.

17) J.S. Fraser, R. L. Sheffield, E. R. Gray, NIM A250, 71-76, 1986.

18) B. E. Carlsten New Photoelectric Injector Design for the Los Alamos XUV FEL Accelerator, NIM A285, 313-319, 1989.

19) E. Chevallay, J. Durand, S. Hutchins, G. Suberluq, M. Wurgel, NIM A340,146, 1994.

20) I. Will, P. Nickles, W. Sandner, A Laser System for the TESLA Photo-Injector, internal design study, Max-Born-Institut, Berlin 1994.

21) K. T. McDonald, Design of the Laser-Driven RF Electron Gun for the BNL Accelerator Test Facility, DOE/ER/3072-43, 1984.

22) Josef Feldhaus, Joerg Rossbach and Hans Weise, Freie-Elektronen-Laser On Spektrum der wissenschaft in Feb. 1998