Free-electron laser:

Free-electron laser FELIX at FOM (Nieuwegein)

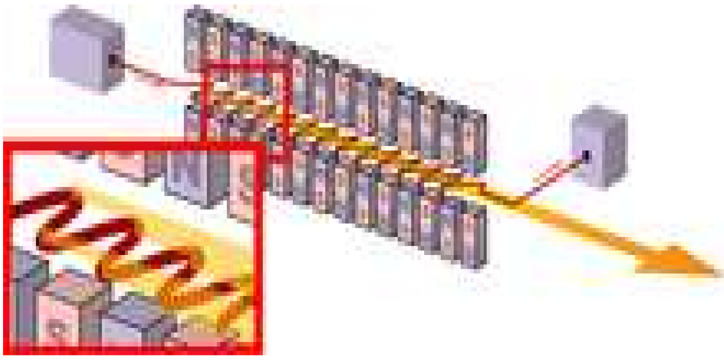
Introduction :

A free-electron laser, or FEL, is a laser that shares the same optical properties as conventional lasers such as emitting a beam consisting of coherent electromagnetic radiation which can reach high power, but which uses some very different operating principles to form the beam. Unlike gas, liquid, or solid-state lasers such as diode lasers, in which electrons are excited in bound atomic or molecular states, FELs use a relativistic electron beam as the lasing medium which moves freely through a magnetic structure, hence the term *free electron.*[1] The free-electron laser has the widest frequency range of any laser type, and can be widely tunable,[2] currently ranging in wavelength from microwaves, through terahertz radiation and infrared, to the visible spectrum, to ultraviolet, to X-rays.[3]

Free-electron lasers were invented by John Madey in 1976 at Stanford University. The work emanates from research done by Hans Motz and his coworkers who built an undulator at Stanford in 1953 using the wiggler magnetic configuration which is at the heart of a free electron laser. Madey used a 24 MeV electron beam and 5 m long wiggler to amplify a signal. Soon afterward, other laboratories with accelerators started developing such lasers.

A Free Electron Laser generates tunable, coherent, high power radiation, currently spanning wavelengths from millimeter to visible and potentially ultraviolet to x-ray. It can have the optical properties characteristic of conventional lasers such as high spatial coherence and a near diffraction limited radiation beam. It differs from conventional lasers in using a relativistic electron beam as its lasing medium, as opposed to bound atomic or molecular states, hence the term free-electron.

Beam creation :



Free electron laser schematic of operation

Undulator of FELIX

To create a FEL, a beam of electrons is accelerated to almost the speed of light. The beam passes through the FEL oscillator, a periodic transverse magnetic field produced by an arrangement of magnets with alternating poles within a optical cavity along the beam path. This array of magnets is sometimes called an undulator, or a "wiggler", because it forces the electrons in the beam to follow a sinusoidal path. The acceleration of the electrons along this path results in the release of photons (synchrotron radiation). Since the electron motion is in phase with the field of the light already emitted, the fields add together coherently. Whereas conventional undulators would cause the electrons to radiate independently, instabilities in the electron beam resulting from the interactions of the oscillations of electrons in the undulators and the radiation they emit leads to a bunching of the electrons, which continue to radiate in phase with each other.[4] The wavelength of the light emitted can be readily tuned by adjusting the energy of the electron beam or the magnetic field strength of the undulators.

Accelerators

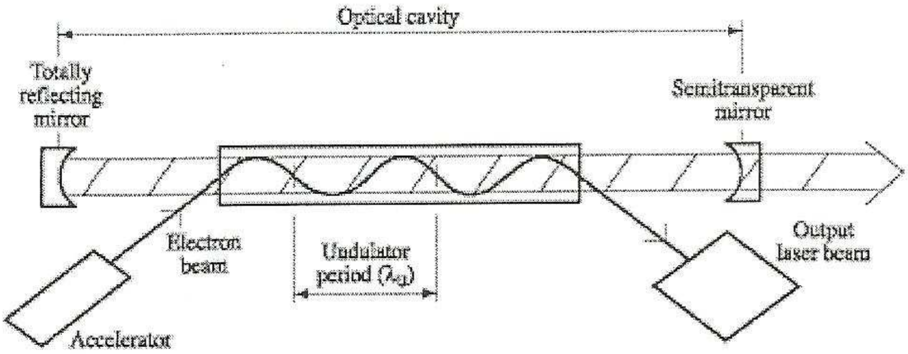


Fig. 2 Typical FEL layout (single passage)

Today, a free-electron laser requires the use of an electron accelerator with its associated shielding, as accelerated electrons are a radiation hazard. These accelerators are typically powered by klystrons, which require a high voltage supply. The electron beam must be maintained in a vacuum which requires the use of numerous vacuum pumps along the beam path. While this equipment is bulky and expensive, free-electron lasers can achieve very high peak powers, and the tunability of FELs makes them highly desirable in several disciplines, including medical diagnosis and nondestructive testing.

X-ray uses

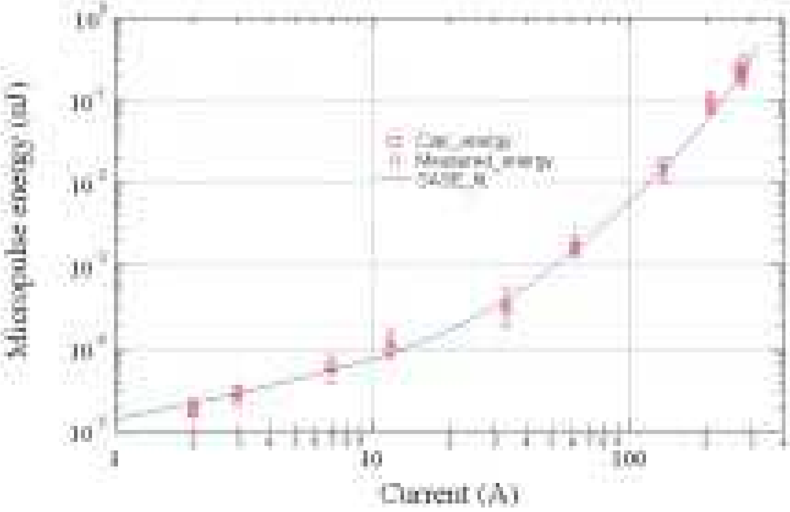
The lack of suitable mirrors in the extreme ultraviolet and x-ray regimes prevents the operation of a FEL oscillator; consequently, there must be suitable amplification over a single pass of the electron beam through the undulator to make the FEL worthwhile. X-ray free electron lasers use long undulators. The underlying principle of the intense pulses from the X-ray laser lies in the principle of self-amplified stimulated emission (SASE), which leads to the microbunching of the electrons. Initially all electrons are distributed evenly and they emit incoherent spontaneous radiation only. Through the interaction of this radiation and the electrons' oscillations, they drift into microbunches separated by a distance equal to one radiation wavelength. Through this interaction, all electrons begin emitting coherent radiation in phase. In other words, all emitted radiation can reinforce itself perfectly whereby wave crests and wave troughs are always superimposed on one another in the best possible way. This results in an exponential increase of emitted radiation power, leading to high beam intensities and laser-like properties.[5] Examples of facilities operating on the SASE FEL principle include the Free electron LASer (FLASH) in Hamburg, the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory, the European x-ray free electron laser (XFEL) in Hamburg, the SPring-8 Compact SASE Source (SCSS), the SwissFEL at the Paul Scherrer Institute (Switzerland) and, as of 2011, the SACLA at the RIKEN Harima Institute in Japan.

One problem with SASE FELs is the lack of temporal coherence due to a noisy startup process. To avoid this, one can "seed" an FEL with a laser tuned to the resonance of the FEL. Such a temporally coherent seed can be produced by more conventional means, such as by high-harmonic generation (HHG) using an optical laser pulse. This results in coherent amplification of the input signal; in effect, the output laser quality is characterized by the seed. While HHG seeds are available at wavelengths down to the extreme ultraviolet, seeding is not feasible at x-ray wavelengths due to the lack of conventional x-ray lasers. In late 2010, in Italy, the seeded-FEL source FERMI@Elettra http://www.elettra.trieste.it/FERMI/ has started commissioning, at the Sincrotrone Trieste Laboratory. FERMI@Elettra is a single-pass FEL user-facility covering the wavelength range from 100 nm (12 eV) to 10 nm (124 eV), located next to the third-generation synchrotron radiation facility ELETTRA in Trieste, Italy. The advent of femtosecond lasers has revolutionized many areas of science from solid state physics to biology. This new research frontier of ultra-fast VUV and X-ray science drives the development of a novel source for the generation of femtosecond pulses.

Test-stand for High-gain SASE Expts.

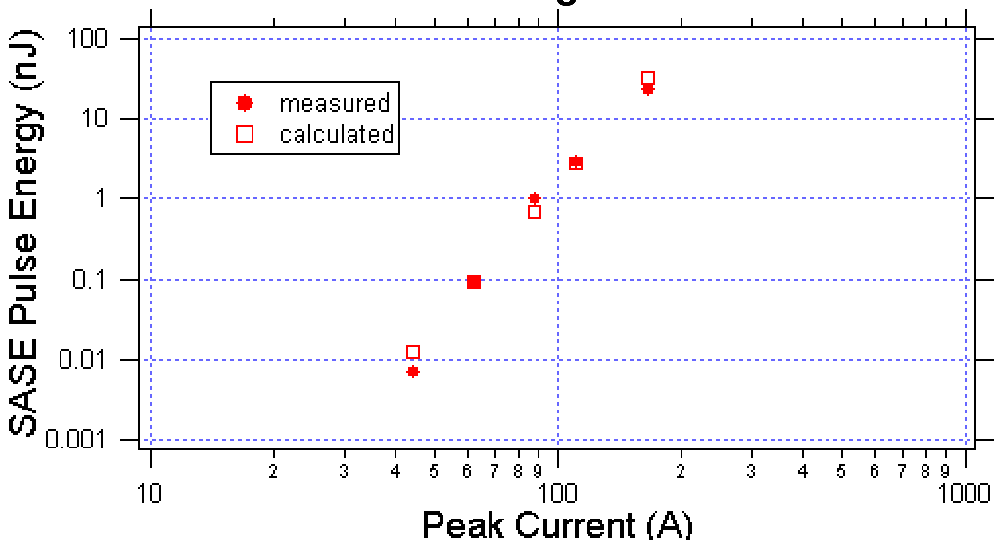
- **High-brightness electron beam**
- **Diagnostics for electrons and photons**

First Measurement of Large SASE Gain



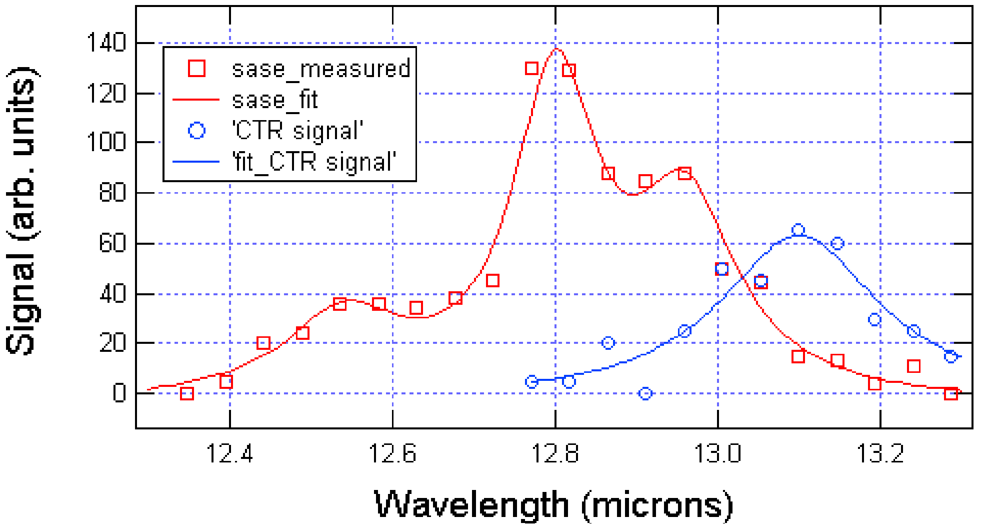
l Gain = 300 for the one-meter undulator

Measurement of Largest SASE Gain



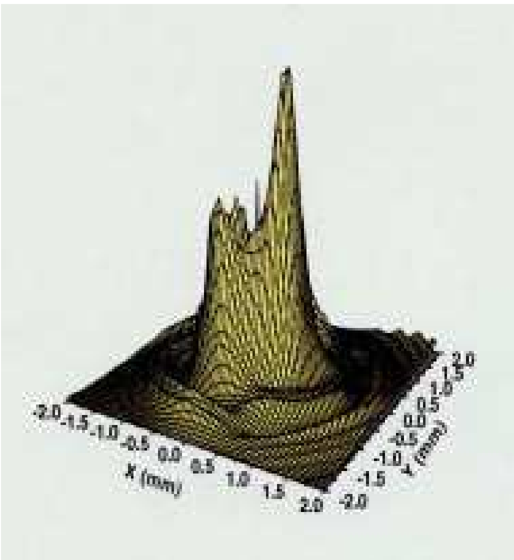
l Gain = 10^5 for the two-meter undulator

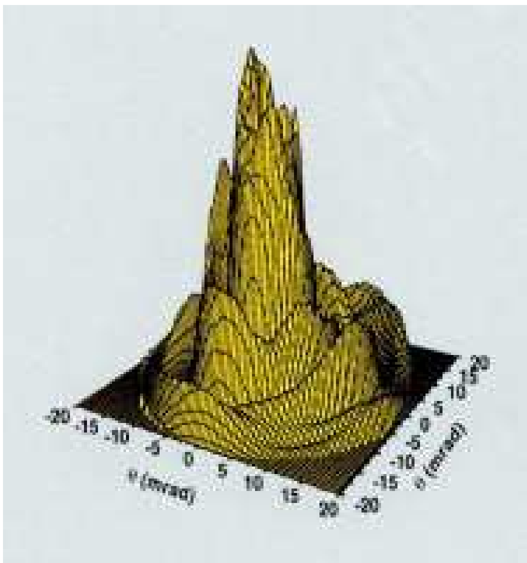
Observation of SASE-induced bunching

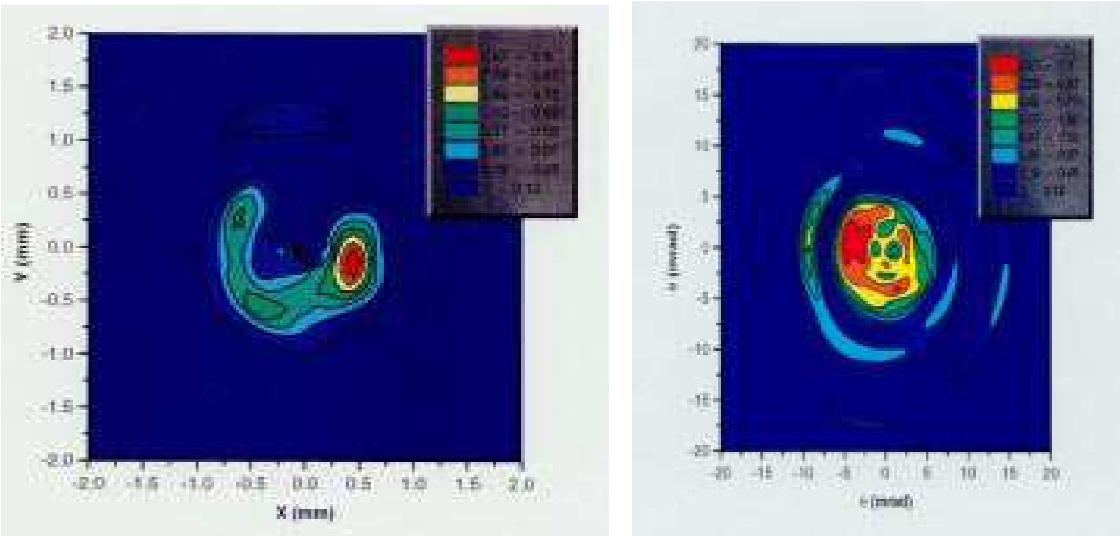


- **Observation of coherent transition radiation**
- **Results corroborate SASE measurements**

SASE Startup Studies







Transverse power distribution for the UCLA experiment predicted by FAST in the low gain regime

The Pendulum Model:

Many features of the dynamics of free electron lasers can be understood using a simple pendulum model. This model comes about because the electromagnetic wave (i.e., the laser field) and the magnetic field of the wiggler act in tandem on the electron to produce a sinusoidal potential similar to that of a pendulum in the earth's gravitational field,

$$|A|(1- \cos(\xi+\phi)).$$

The constant *A* will depends on a number of FEL parameters including the distance between the wiggler magnets, the strength of the wiggler field, and the energy of the injected electrons. But most importantly, *A* is proportional to the laser field strength. Imagine that an electron is part way up the potential well but falling toward the potential minimum at theta =0. The energy released by the electron increases the laser field and consequently lowers the minimum further. Conversely, electrons moving away from the potential minimum up the potential well decrease the laser field. Since many electrons are injected into the FEL simultaneously, the dynamics of the system can become very complex indeed.[6]

Equations of Motion:

Both the equations of motion for individual electrons,

$$d^2 \xi/dt^2 = |A| \sin(\xi+\phi)$$

and the wave equation for the laser field,

$$d A/ dt = -J \langle \exp(-i \xi)\rangle$$

are solved by the FEL applet embedded in this document. The non-dimensional scaled parameters, *A* and J, are proportional to the optical field strength and the current density, respectively. The beam current density, J, determines the rate of change of the laser field, A. The phase of the laser field phase, ϕ, is of course the phase of the complex scalar, *A*. The position of the electron is determined by the pondermotive (or electron) phase, ξ. It is a measure of the position of an electron with respect to the beat wave between the electromagnetic and wiggler fields,

$$\xi=(k_u-k)z - \omega t.$$

The pendulum FEL model is valid for both weak or strong optical fields and for high or low gain. The theory does not include space charge effects, i.e., the electrons do not interact among themselves, nor does it include any off axis field dependence, i.e., the optical field is smoothly varying and one dimensional. The theory also assumes that the fractional energy change of the electron in passing through a single wiggler magnet is small.[7]

Application;

1- Medical uses

Research by Dr. Glenn Edwards and colleagues at Vanderbilt University's FEL Center in 1994 found that soft tissues like skin, cornea, and brain tissue could be cut, or ablated, using infrared FEL wavelengths around 6.45 micrometres with minimal collateral damage to adjacent tissue.[8][9] This led to further research and eventually surgeries on humans, the first ever using a free-electron laser. Starting in 1999, and using the Keck foundation funded FEL operating rooms at the Vanderbilt FEL Center, Dr. Michael Copeland and Dr. Pete Konrad of Vanderbilt performed three surgeries in which they resected meningioma brain tumors.[10] Beginning in 2000, Dr. Karen Joos and Dr. Louise Mawn performed five surgeries involving the cutting of a window in the sheath of the optic nerve, to test the efficacy for optic nerve sheath fenestration.[11] These eight surgeries went as expected with results consistent with the routine standard of care and with the added benefit of laser surgery and minimal collateral damage. A review of FELs for medical uses is given in the 1st edition of Tunable Laser Applications.[12]

Since these successful results, there have been several efforts to build small, clinical lasers tunable in the 6 to 7 micrometre range with pulse structure and energy to give minimal collateral damage in soft tissue.[*citation needed*] At Vanderbilt, there exists a Raman shifted system pumped by an Alexandrite laser.[13]

At the 2006 annual meeting of the American Society for Laser Medicine and Surgery (ASLMS), Dr. Rox Anderson of the Wellman Laboratory of Photomedicine of Harvard Medical School and Massachusetts General Hospital reported on the possible medical application of the free-electron laser in melting fats without harming the overlying skin.[14] It was reported that at infrared wavelengths, water in tissue was heated by the laser, but at wavelengths corresponding to 915, 1210 and 1720 nm, subsurface lipids were differentially heated more strongly than water. The possible applications of this selective photothermolysis (heating tissues using light) include the selective destruction of sebum lipids to treat acne, as well as targeting other lipids associated with cellulite and body fat as well as fatty plaques that form in arteries which can help treat atherosclerosis and heart disease.[15]

2- Military uses :

FEL technology is being evaluated by the US Navy as a good candidate for an anti aircraft and missile directed-energy weapon. Significant progress is being made in raising FEL power levels (the Thomas Jefferson National Accelerator Facility's FEL has demonstrated over 14 kW)[16] and it should be possible to build compact multi-megawatt class FEL weapons.[17] On June 9, 2009 the Office of Naval Research announced it had awarded Raytheon a contract to develop a 100 kW experimental FEL.[18] On March 18, 2010 Boeing Directed Energy Systems announced the completion of an initial design for U.S. Naval use.[19] A prototype FEL system has since been demonstrated with a full-power prototype scheduled by 2018.[20]

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