FEL OSCILLATORS

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Abstract

FEL Oscillators have been around since 1977 providing not only a test bed for the physics of Free Electron Lasers and electron/photon interactions but as a workhorse of scientific research. More than 30 FEL oscillators are presently operating around the world spanning a wavelength range from the mm region to the ultraviolet using DC and rf linear accelerators and storage rings as electron sources. The characteristics that have driven the development of these sources are the desire for high peak and average power, high micropulse energies, wavelength tunability, timing flexibility, and wavelengths that are unavailable from more conventional laser sources. Substantial user programs have been performed using such sources encompassing medicine, biology, solid state research, atomic and molecular physics, effects of non-linear fields, surface science, polymer science, pulsed laser vapor deposition, to name just a few. Recently the incorporation of energy recovery systems has permitted extension of the average power capabilities to the kW level and beyond. Moreover the use of collective radiation and Thompson/Compton scattering has produced substantial fluxes of THz radiation, X-rays, and gamma rays. This paper will discuss at a summary level the physics of such devices, survey existing and planned facilities, and touch on the applications that have driven the development of these popular light sources.

INTRODUCTION

Like other lasers, the FEL consists of a gain medium, a means to put energy into it, a means for dealing with the spent energy, and an optical system to appropriately direct the photons produced. The gain medium in the FEL is the electron beam produced by various types of accelerator. Electron accelerators are a relatively well-developed technology and the engineering involved is well known; however, the FEL puts extreme demands on the quality of the electron beam and care must be taken of the details of accelerator design. Indeed, the feasibility of FEL designs have always hinged on the beam brightness produced by the accelerator. The output of the FEL also mimics to a great extent the temporal characteristics of the electron source so that the desired radiation characteristics influence the choice of accelerator technology.

In wavelength regions where mirror technology is robust, FEL oscillators are the preferred approach because the lower gain required in such systems relaxes demands on peak current and electron beam quality. Figure 1 illustrates the components of such a FEL oscillator. Oscillators have been the primary approach for FELs operating in the mm wave to near UV range for 25 years. A large number are in operation around the world and they have been highly successful as scientific instruments

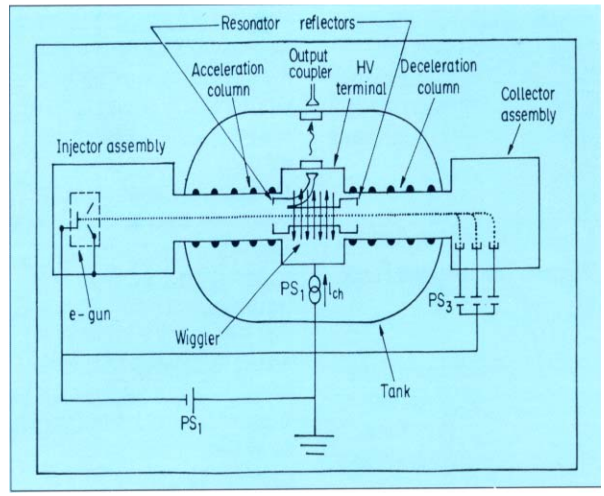

Figure 1: The mm wave FEL oscillator at Tel Aviv University utilizes a wiggler at high voltage with current recovery of the electron beam for CW operation at high power. Figure courtesy A. Gover.

for users. While much new effort in the FEL community is focused on pushing FEL performance to operation in the VUV and X-ray region where amplifiers are more appropriate, FEL oscillator user facilities are expected to remain a major factor in light source applications.

ATTRIBUTES OF FEL OSCILLATORS

If the small signal gain is greater than the round trip losses in the optical cavity then the signal will naturally grow to saturation. For stable operation and to extract significant fractions of the electron beam energy it is generally desirable to have the small signal gain exceed 3 times the cavity losses including outcoupling. This is not a severe restriction since mirrors can be fabricated with less than 1% loss from the IR down to around 250 nm in wavelength. Thus practical FEL designs can exist where the signal pass gain is only a few percent although more gain is certainly advisable. Since the gain can be so low, injector brightness requirements can be comparatively modest, the wiggler can be short, and its tolerances modest. Over most of its operating range the FEL output of such a system is stable and low noise. Most systems operate with a Fourier transform limited bandwidth. If desired, wavelength selectivity can be driven by the mirror optical coating reflectivity. Another advantage is that the optical mode produced is well-defined by the optical cavity and the spatial filtering provided by the small gain medium.

These advantages come at a price though even beyond the requirement for reflective mirrors. For example, in an oscillator the FEL determines lasing wavelength, not you. It generally stabilizes at the point of maximum net gain in the system although there are exceptions to this if the maximum saturated gain exists in a frequency "island" inaccessible to the starting oscillation frequency. Another disadvantage is that the accelerator must produce a stable pulse train of electrons; one pulse isn't enough. The pulse train must continue long enough for the optical mode to grow to saturation.

There is also the requirement for getting useful optical power out of the cavity; either a partially transparent mirror, reflective window, or grating must be used, or some physical method to out-couple the power must be employed, e.g., a hole in the mirror or a scraper. And last, but not least, the optical resonator cavity length and transverse alignment must meet stringent stability requirements.

Since the wavelength range desired guides one toward a particular accelerator approach and such accelerator approach determines many of the macroscopic characteristics of the FEL output we will present below a set of examples of FEL oscillators arranged by wavelength starting with the longest wavelength output and moving toward the UV. A more complete listing of operational FELs can be found in the annual proceedings of the International Free Electron Laser Conference [1].

FIR FEL Oscillators

At wavelengths ranging from millimeter waves to the mid-infrared, DC accelerators such as pulse line accelerators and modulators can be used to accelerate the beam from a either a thermionic or field emission cathode. Induction linacs have been used at these wavelengths as well. At these longer wavelengths, the FEL gain can be very high and very high peak powers can be produced. Typically only electrostatic accelerators produce beam pulses long enough for oscillator to be practical. DC sources also have the potential of producing high average power at high efficiencies if some means of recovering the beam energy or current such as depressed collectors is used.

Electrostatic accelerators can, in principal, produce CW beams; however, in order to do so it is necessary to recycle the current in the spent beams to replenish the charging current. In practice, CW operation requires the recovery of better than 99% of the spent current. This has been done at high efficiency [2] and offers the promise of achieving CW operation [3]. An alternative is to produce the beam near ground potential and have the wiggler at high positive potential and then recover the beam at ground again (see Figure 1). Two systems are under test to utilize this approach to produce high average power at 130-250 GHz for heating of fusion research plasmas [4,5] Operation on the third harmonic has yielded 30 micron output with modest voltages [6].

Near IR Oscillators

Operation at wavelengths from the near infra-red IR through the visible requires beam energies in excess of 10 MeV. For these applications, the most commonly used accelerator is a conventional copper RF linac. Examples of this technology are the S-band (2856 MHz) system at Vanderbilt University, a large set of wigglers on the FELI facility at Osaka University, the FELIX facility at FOM in the Netherlands, and many others around the world using conventional pulsed linac technology with injectors that typically produce 10 μs macropulses with a pulse repetition frequencies (PRF) of up to 60 Hz.

These have limited duty factors due to ohmic heating in the cavities by the microwaves. A copper machine at Boeing Aerospace pushed this technology to its fullest with a 433 MHz accelerator that is capable of cw operation and has demonstrated a 25% duty factor. Nearly 130 ma of high quality macropulse current was produced at over 1 nanocoulomb per bunch [7].

Highly successful user facilities have been constructed at Osaka University (FELI)[8], FOM (FELIX)[9], Science University of Tokyo (FEL-SUT)[10], and Vanderbilt[11].

FELI

An example of the success that can be achieved with very high energy copper linacs is the lasing at 278 nm achieved from the 165 MeV linac at FELI in Japan [8]. Wigglers in this facility have operated at wavelengths from 80 to 0.28 microns. The laser produced 1.5 mJ/pulse in 24 μs macropulses at 20 Hz PRF. The lasing achieved here is the shortest oscillator wavelength to date on a linac-driven system. Among the extensive studies carried out at the FELI facility in Japan are resonant excitations of molecular vibrations [12], band discontinuities of semiconductor heterojunctions [13], and isotope separation [14]. The tunability, power, and pulse variability of the FEL has made it an efficient biophysical research tool [15].

FELIX

Arguably the most productive IR User facility in the world is the FELIX facility at FOM in the Netherlands. There are two lasers on the system which have been extensively used for studies in solid state dynamics, atomic clusters, and magnetic materials. Felix offers lasing from 16-250 um or 4-30 um from two FELs at 10 Hz with 100 mJ produced per macropulse. The machine is stable enough that the users typically operate the machine themselves. A particular success of the facility is in incorporating a number of enhancements to the use of photons such as synchronized pulse slicing of individual micropulses as well as other synchronized lasers. A substantial set of publications can be reviewed from their web site [16]. One particularly interesting result has been the identification of titanium carbide as a constituent of interstellar plasmas. An upgrade presently in construction will permit intracavity tests at an internal focus. The high fields produced will permit the study of a number of non-linear phenomena.

Jefferson Lab FEL

An alternate to copper accelerator technology capable of CW or long macropulses is the superconducting RF linac structure (SRF) typified by the Continuous Electron Beam Accelerator (CEBA) at Thomas Jefferson National Accelerator Facility which produces 4 GeV electron beams for nuclear physics research using 1497 MHz cavities operated at 2K. Ohmic losses are reduced to negligible levels with the SRF structures (6 W/cavity at typical gradients) while maintaining high acceleration gradients (5 to 18 MV/m).

The IR Demo was completed in September 1998. The injector is the critical technology for operation of systems such as this; it must produce high average currents at high brightness. This system utilizes a DC photocathode operating at 320 kV to produce a 74.85 MHz pulse train of 60 pC. This gun produces the highest average brightness of any injector gun in the world and delivered in excess of 5.3 kilocoulombs from a single GaAs crystal at 1% quantum efficiency operating in the green from a doubled Nd:YLF laser beam. The IR Demo beam was accelerated to between 36 and 48 MeV and produced over 2 kW of CW average power[17]. In addition, the system produced 4 watts of power lasing on the fifth harmonic at 1 micron. Third harmonic operation at 1 micron achieved 300 W CW [18] and, even beyond this, conversion to > 60 W of green and > 10 W of UV at high efficiency in doubling, tripling and quadrupling crystals. Up to 10^9 photons/sec of Thompson scattered X-rays in the 5 to 15 keV range are produced when the FEL pulse scatters off subsequent electron bunches. The system also synchronously produces $>10^4$ more THz power (50 W) in sub-picosecond pulses than any other source [19].

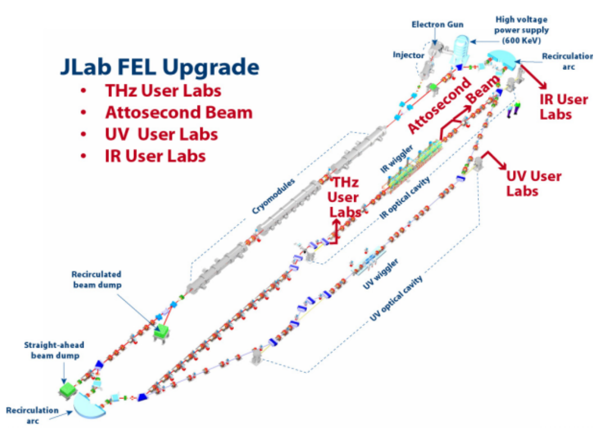

Figure 2: The Jefferson Lab IR Upgrade FEL oscillators utilize energy recovery of the spent electron beam for high efficiency and CW operation. Output ports will provide user light at a number of wavelengths ranging from X-rays down to terahertz. This is the highest average power tunable laser in the world.

An Upgrade of the system now in commissioning will produce continuously over 10 kW in the IR from 1 to 14 microns and over 1 kW in the 250 to 1000 nm range (Figure 2). The system uses energy recovery of the beam as demonstrated in the IR DEMO to reduce required rf power, virtually eliminate activation of components, and reduce power handling requirements on the dump. The machine will deliver beams of high power THz, IR, and UV to a set of User Labs for scientific and applied studies. Such studies on the IR Demo have already been extremely successful in exploring vibrational dynamics of interstitial hydrogen in crystalline silicon, carbon nanotubes, and pulsed laser deposition [20, 21]. Future applications will include those as well as microengineered structures, non-linear dynamics in atomic clusters, and metal amorphization. This machine is viewed as the first of a new category of high power, high brightness light sources called Energy Recovering Linacs (ERLs) with the potential to extend beyond the performance of third generation synchrotrons in both brilliances as well as offering the capability of femtosecond light pulses for dynamics studies. [22-24] (See Figure 3).

A similar energy recovery effort for high power generation is underway at the Japan Atomic Energy Research Institute (JAERI)[25,26].

Stanford Superconducting Accelerator FELs

The original FEL oscillator work was performed on the pioneering Stanford Superconducting Accelerator [27] and since that time the facility has been a center for research into FELs and their application [28,29]. The focus of the facility over the last decade has been the utilization of the FEL with a wide range of other laser sources to perform materials research with picosecond pulses. At present two FELs are installed on the linac which is undergoing an upgrade of the accelerator structures. The FIR FEL produces 1 W of 15 - 85 micron light from a tunable 25 period electromagnetic wiggler.

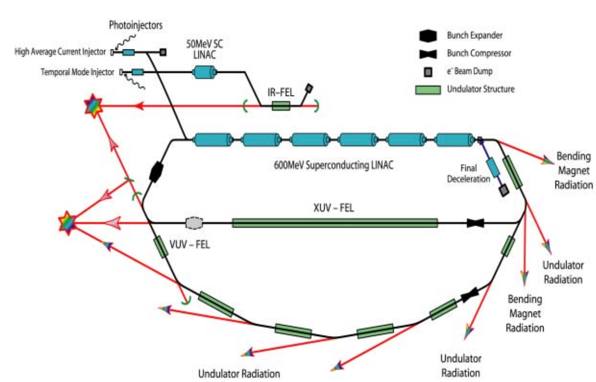

Figure 3: The Proposed 4GLS System at Daresbury Laboratory (for "Fourth Generation Light Source"). The Facility will consist of several FELs and an Energy Recovering Linac with a SASE FEL capability. Figure courtesy E. Seddon.

The MIR system produces 2 W in the 3 - 15 micron range from a 12.68m optical cavity around a 72 period hybrid wiggler of 31 mm wavelength. The FELs can be made to lase on alternating macropulses with essentially independent control of the optical output. Key studies at Stanford include second order nonlinear susceptibility of the conduction band and valence band quantum well (QW) structures extracted from the interference between second harmonic fields of QWs and GaAs substrate as determined by the azimuthal dependence of the second harmonic power. This was the first demonstration of difference frequency generation of mid-IR in any QW [30]. Groups at Stanford also studied vibrational dynamics in glass forming liquids. These were the first vibrational photon echo experiments and first comprehensive temperature dependent pump probe measurements on any condensed matter system [31].

In Dresden, construction of a superconducting FEL called ELBE is proceeding along the same lines[32].

UV FEL OSCILLATORS

In addition to UV oscillators on linac based systems such as FELI, the JLab Upgrade, and the proposed 4GLS, storage rings can be a cost effective alternative to producing the energies of up to a few GeV for operation at wavelengths in the ultraviolet spectrum [33]. The gain of the FEL drops inversely with the energy and mirror technology becomes increasingly difficult below 250 nm so that at some point oscillators become non-viable. The time to damp the energy spread introduced in the beam limits the average power that can be produced [34], although typically ring based FELs can operate in either a CW mode or as a high pulse power "Q-switched" mode where lasing undergoes a relaxation oscillation by damping between high power pulses.

Duke UV Ring

An example of such a storage ring system is at Duke University [35]. The ring has a circumference of 107.46m and provisions for two straight sections, and an energy range of 0.25 to 1.2 GeV. The machine can accommodate average currents of up to 115 mA. The OK4 wiggler system lased successfully at 345 nm beginning in December 1996 producing 150 mW and small signal gains of nearly 10%. This system has since lased at wavelengths as short as 193 nm. This system also demonstrated Compton scattering of the FEL light to produce gamma rays at up to 250 MeV which are used for fundamental nuclear physics research (Figure 4). While other lasers can be used for Compton scattering, the natural synchronism and physical overlap between the electron beam and light produced in the FEL is a major advantage for using the FEL light itself. Other FEL storage rings have also achieved notable success: VEPP3 [36], Super-ACO [37], UVSOR [38], and NIJI-IV [39] and ELETTRA [40].

SUMMARY

The discussion above illustrates the breadth of FEL oscillators' capabilities. These facilities continue to grow and produce increasing capabilities for basic and applied studies in biological, solid state, atomic and molecular physics. The wavelength ranges over which oscillators are the optimal approach include the rich area of vibrational and phonon activity of solids. Over much of the operational range of these devices no other system offers the pulse energy, or tuning bandwidth that FELs permit. It is expected that FEL oscillators will continue to be productive research tools for many years to come.

As shown especially in facilities such as FELIX and the Stanford FELs, manipulations of the optical beam such as noise eaters, cavity dumping, loss modulation, cavity length modulation, intensity mapping, mode selection, mode locking, spectral filtering etc., can provide substantial enhancements for user experiments and need further development. These are all pretty well established in conventional lasers but still largely undeveloped in FELs to the same level seen in conventional lasers.

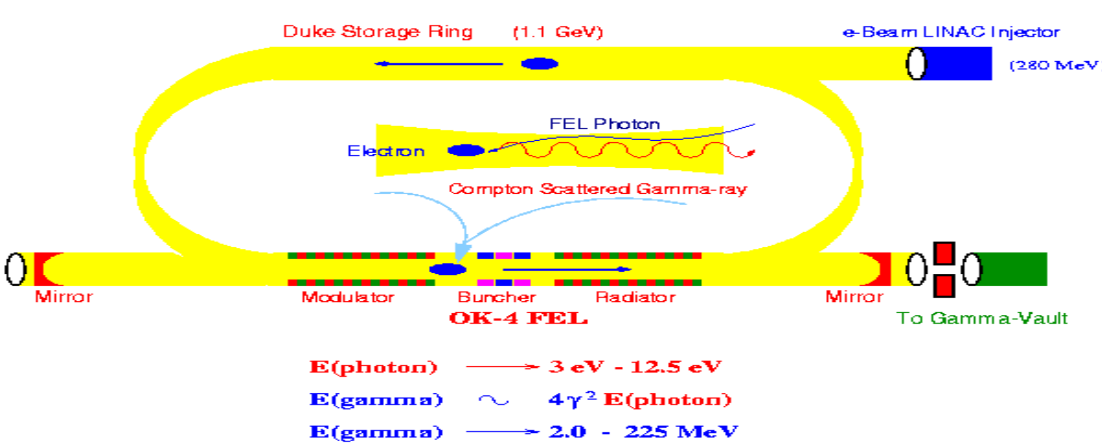

Figure 4: Setup of the DUKE OK-4 Compton gamma ray source. Figure courtesy V. Litvinenko

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