EUROPEAN FREE-ELECTRON LASER USER FACILITIES

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Abstract

In a free-electron laser (FEL), undulator radiation is captured in an optical cavity and amplified typically by eight orders of magnitude. The feature of continuous tunability over a wide spectral range, in combination with a high peak power, makes the FEL a unique tool for experiments in various scientific disciplines. Two FEL user facilities are operational on the European scene, namely FELIX at Nieuwegein and CLIO at Orsay. Together these FELs cover the spectral range from 2 to 110 μm, which puts them in a prominent position worldwide. In addition, there are user-oriented FEL projects at Frascati and Darmstadt. The performance of these facilities is discussed.

1. INTRODUCTION

The operation of a free-electron laser (FEL) involves a combination of techniques from synchrotron radiation sources and regular lasers [1]. Spontaneous radiation is produced by relativistic electrons travelling through the field of an undulator magnet. This radiation is weak and incoherent, because the waves emitted by electrons having a longitudinal separation of half a wavelength interfere destructively. Coherence is induced by capturing the radiation in an optical cavity. The ponderomotive force associated with the stored field induces a longitudinal modulation of the electron density, with peaks separated by an optical wavelength. This partly changes destructive interference into constructive interference and, on multiple passes through the cavity, leads to the build-up of an intense, coherent laser field. At saturation, the stored power typically is eight orders of magnitude more intense than the initial undulator radiation. As in other lasers, a fraction of the stored power is coupled out on each cavity roundtrip.

The FEL wavelength is determined by macroscopic parameters (namely the electron energy and the period and strength of the undulator field) rather than by the microscopic properties of atoms. This striking difference with other lasers has the consequence that an FEL can be designed to operate at 'any' wavelength, while at the same time continuous wavelength scans can be made by adjustment of one of the macroscopic parameters. However, there is the drawback that an FEL is a much more bulky and expensive device than other lasers, mainly due to the electron accelerator and associated equipment. This makes the FEL a less suitable candidate for operation in the near-infrared, visible and near-ultraviolet, in view of the wide variety of bench-top lasers that are available commercially in this part of the spectrum. The situation is different in the far-infrared and vacuum-ultraviolet. There is a growing awareness that there are two clear 'niches' for the FEL: the far-infrared spectral range above roughly 10 μm and the vacuum-ultraviolet below 100 nm.

2. FEL USER FACILITIES

The operation of FEL user facilities in the infrared part of the spectrum is addressed in this paper. Following the pioneering experiments by Madey and coworkers at Stanford in the seventies [2], several laboratories worldwide have made an effort to obtain the excellent electron beam quality needed for FEL oscillation: high brightness, small energy spread, long macropulse length, very good temporal stability, etc. This has pushed the state of the art in accelerator technology. Right now, sufficient experience with infrared FELs has been obtained to provide the reliability needed for application in user experiments. A number of FEL user facilities have been proposed since the mid-eighties; several are now operational and others are under construction.

The oldest user facility, at Santa Barbara in the USA [3], came on the air in 1986. This facility operates in the far-infrared spectral range from 60 μm to several mm. An electrostatic accelerator is used to produce a beam of electrons at a maximum energy of 6 MeV. The main restriction is the limited current available from VandeGraaff generators, at most a few mA. This is considerably below the minimum current required to overcome the threshold for lasing, typically a few A. The problem is solved by recirculation of the electron beam, *i.e.* by directing the electrons back into the high-voltage terminal after they have traversed the undulator. The generator then serves to supply the loss current only. On the European scene, similar devices have been proposed by groups at Oxford, Lille and Dijon but none of these projects have been funded. Nevertheless, in a pilot experiment the machine at Oxford has produced radiation in the 350-1860 μm spectral range, using a so-called Smith-Purcell configuration (*i.e.* a metal grating instead of a regular undulator magnet) [4].

Higher electron beam energies than at Santa Barbara and, hence, shorter wavelengths, can be obtained with an rf-linac, either at room temperature or superconducting. Five linac-based user facilities are operational right now, two in Europe (at Orsay and Nieuwegein) and three in the USA (at Stanford, Durham and Nashville) [5]. On the European scene, a linac-based user FEL is being commissioned at Darmstadt, and a

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project at Trieste is in the proposal stage. In addition, a microtron-based FEL is operational at ENEA, Frascati. These European projects are discussed further on. An overview of the spectral range covered by, or anticipated for, the various FEL user facilities worldwide is given in Fig. 1. Note that projects dedicated to basic research on the FEL itself (for instance at Bruyères-le-Châtel and Twente) are not shown.

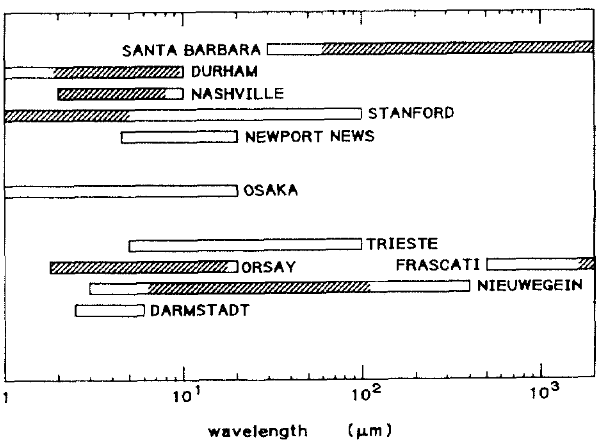

Figure 1. Overview of the spectral range covered by FEL user facilities worldwide. Hatched bars: operational. Open bars: under construction or proposed.

3. PULSE FORMAT

The output of an rf-accelerator (either a linac or a microtron) consists of short bunches with a duration of a few ps, which form a train, the so-called macropulse. The laser beam mimics this temporal structure: since each electron bunch produces an optical 'micropulse', the laser output consists of short pulses having the same repetition frequency as the electron bunches. The duration of the optical micropulses can be manipulated by a change of the cavity length, which influences the synchronism of stored pulses and electron bunches [6]. The cavity is depleted after each electron macropulse and the laser power has to build up again from spontaneous emission on the next macropulse.

It is important to realize that the 'optimum' pulse format depends very much on the application in question. A short micropulse duration is important for studies of fast phenomena [7]; in fact, the quasi-continuous laser output of electrostatic accelerator based FELs (several tens of μs) is undesirable for many applications. However, a short pulse also implies a large bandwidth and, hence, less selectivity. A high micropulse repetition frequency leads to a high average power, but too high a frequency may be a disadvantage in studies of time-dependent phenomena having a relaxation time longer than the time between successive pulses. A high repetition frequency may also lead to unwanted sample heating. On a different matter, a high repetition frequency results in a large number of optical pulses in the laser cavity, and this permits phase locking by means of intracavity interferometric devices. This offers the possibility to select truly narrow-band radiation from the laser output [8], which is important for application in high-resolution spectroscopy.

As regards the macropulse duration, a long macropulse permits on-line stabilization of laser parameters, for instance the wavelength or output power. This is a particularly attractive feature of superconducting-linac based FELs. A long macropulse also results in a high average power, but the latter may again lead to unwanted sample heating. There are similar considerations for the macropulse repetition frequency.

It may be clear from this discussion that it would be difficult to accommodate all user experiments on a single machine. Instead, it is much more attractive to operate a network of facilities with different wavelength coverage and pulse format. It will be discussed in Sec. 4 that the various facilities on the European scene do indeed provide this kind of complementarity. The case for multiple FELs is corroborated by the fact that, in contrast to synchrotron radiation facilities, an FEL is essentially a single-user machine (unless two experiments require exactly the same laser parameters).

4. THE EUROPEAN SCENE

The Free Electron Laser for Infrared eXperiments (FELIX) at the FOM-Institute in The Netherlands uses an electron beam with an energy up to 45 MeV [9]. The injection stage of the accelerator consists of a thermionic electron gun (a triode) which is modulated at 1 GHz, a 1-GHz subharmonic pre-buncher, and a 3-GHz buncher. The electron energy after the buncher is 3.8 MeV. Acceleration to a maximum energy of 25 MeV takes place with a normal-conducting 3-GHz linac. Behind the linac, the electrons are either bent out of the beam line for injection into an undulator (FEL-1) or they are injected into a second linac. After acceleration to a maximum energy of 45 MeV, they are then injected into a second undulator (FEL-2). This approach permits coverage of a wide spectral range, presently from 5 to 110 μm. With FEL-1, laser oscillation was achieved for the first time in mid 1991 and FEL-2 became operational one year later.

The FEL at LURE-Orsay, CLIO (*Collaboration pour un Laser Infrarouge à Orsay*), came on the air in the same period, early 1992. The set-up of the accelerating system is quite similar to FELIX: a thermionic gridded cathode is followed by a 500-MHz prebuncher, a fundamental 3-MeV buncher and an S-band linac. The electron energy is adjustable between 32 and 58 MeV. An important difference with FELIX is the pulse format. FELIX presently operates at a fixed bunch separation of 1 ns, but the CLIO electron gun is more flexible: the bunch separation can be varied in steps between 4 and 32 ns. The latter value is equal to the cavity roundtrip time, so that just a single optical micropulse is stored. CLIO presently covers the spectral range from 2 to 17 μm [10]. A specific advantage is the presence of the storage ring Super-ACO in the same building. This conceivably permits two-colour experiments using synchrotron radiation and the FEL output.

Both FELIX and CLIO use an undulator consisting of permanent magnets, with the property that the gap between the two parallel rows of magnets can be adjusted on-line. This changes the magnetic field that is 'felt' by the electrons, with the consequence that radiation with a different wavelength is emitted. Gap tuning permits continuous wavelength scans typically over an octave in just a few minutes [10, 11]. The electron energy has to be changed in case a wavelength outside this range is needed. With this unprecedented ease of tunability, an important design objective for both machines has been fulfilled. The tuning range is illustrated in Fig. 2. The figure gives the micropulse energy which is available in the user stations, *i.e.* losses in the transport systems (due to mirror absorption, beam diffraction and misalignment) are taken into account. The corresponding micropulse peak power ranges up to tens of MW.

The third linac-based European FEL project is carried out at Darmstadt in Germany. The FEL is located on a bypass of the superconducting accelerator (S-DALINAC) which came into operation in 1991. This machine has been funded mainly for studies in nuclear physics, but a fraction of the beam time is available for FEL development and (at a later stage) application in user experiments. An important feature of the Darmstadt FEL is the prospect of cw operation; note that FELIX and CLIO operate with macropulses typically of 8 μs duration. This makes the Darmstadt FEL best suited for active stabilization of, for instance, the wavelength. After installation of a pulsed high-current gun and incorporation of a 600-MHz chopper-prebuncher system, spontaneous emission has been observed [12]. Regular lasing has not been obtained yet, an

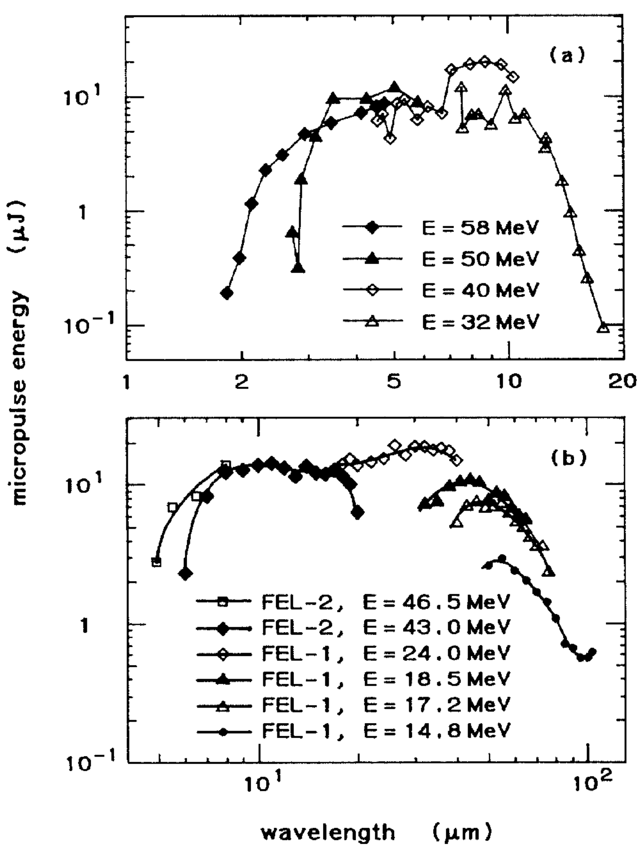

Figure 2. Micropulse energy of CLIO (a) and FELIX (b) as a function of wavelength. Results are shown for different values of the electron beam energy. At a fixed energy, the wavelength is scanned by adjustment of the undulator field.

important constraint being that the laser will operate just above threshold. This is due to the relatively low electron (peak) current. The Darmstadt FEL has been designed to cover the spectral range from 2.5 to 7 μm.

A truly compact FEL is operational at ENEA-Frascati in Italy [13]. This machine, which has dimensions approaching those of table-top laser, uses a microtron to produce an electron beam with an energy of 2.3 MeV. As a consequence of this low energy, the radiation wavelength is in the micro-wave range, 2.1-3.6 mm. This long wavelength necessitates the use of a waveguide to contain the stored wave within the undulator. The system is in the process of being upgraded in order to operate at 5 MeV. In combination with a new undulator, this would bring the wavelength down to 500 μm, whilst maintaining a short micropulse length. Note that the latter is an essential difference from the quasi-cw FEL at Santa Barbara.

Plans for an infrared user FEL (nicknamed FERMI, Free-Electron Radiation and Matching Instrumentation) exist at Trieste [14]. The idea is to use the injector of the synchrotron radiation source ELETTRA, which is idle after the storage ring has been filled, as driver for the FEL. It is planned to operate between 2 and 100 μm, using electrons with an energy of 30-75 MeV. At a later stage, operation at 100 MeV would bring the wavelength down to 0.5 μm.

An overview of the properties of existing and planned European user FELs is given in Table 1.

5. USER OPERATION

Of all European projects, FELIX and CLIO clearly are the only regular user facilities right now. At FELIX, radiation has been provided to users since mid-1992, immediately after the commissioning of FEL-2. In 1993, beam time was made available to users during 26 weeks, involving a total of 1150 hours, and six weeks were used for the in-house programme on FEL physics. Periods of FEL operation were interspersed with periods in which the infrastructure of the user facility was implemented. Right now, the installation of the user facility has been completed and the FEL is sufficiently reliable to aim for operation during 42 weeks each year. The transition to regular two-shift operation was made in mid-1994. This will provide up to 2800 hours of beam time each year.

The situation at CLIO is quite similar. After an already substantial user programme in 1992 and 1993, the plan for 1994 is to operate during 38 weeks, of which 26 weeks are intended for user experiments and 12 weeks for further FEL development. This involves a total of over 2000 hours of beam time each year. A 'run' at CLIO frequently lasts 15 hours, which is possible in part because the users have been taught to control the most important laser parameters. After the FEL has been started up by a machine operator, the user group can straightforwardly change the undulator gap to change the wavelength, or the cavity length to change the micropulse duration. Users of FELIX have the same possibility, but the strategy regarding allocation of beam time is different in the sense that each run lasts eight hours, so that two user groups are served each day.

TABLE 1. Characteristic accelerator (upper panel) and laser (lower panel) properties of existing and planned European FEL user facilities. The laser properties refer to the outcoupled beam.

	ORSAY (CLIO)	NIEUWEGEIN (FELIX)	FRASCATI	DARMSTADT (S-DALINAC)	TRIESTE (FERMI)	
Electron energy	32-58	15-46.5	2.3	30-50	30-75	MeV
Bunch charge	700	200	70	5.2	400	pC
Bunch separation	4-32	1	0.33	100	36	ns
Macropulse duration	8	8	4	cw	8	μs
Macropulse rep. rate	50	10	50	cw	10	Hz
Norm. emittance (90%)	200	100	65	10	290	π μm
Spectral range	2-17	5-110	2100-3600	2.5-7	2-100	μm
Micropulse energy	<50	<20	0.5	0.2	10-20	μJ
Micropulse duration	0.5-6	1-10	60-200	2	2-10	ps
Macropulse power	<12	<20	<1.5	-	<0.5	kW
Average power	<5	<1	<0.3	2	<0.05	W

Although an FEL is essentially a single-user machine (because it is unlikely that two groups have the same requirements on wavelength, micropulse length, etc), it is important to have multiple user stations, where the experimental set-ups can remain in place during periods in which other groups are served. To this end, FELIX and CLIO each have five different stations at present. The laser output is distributed to these stations by means of mirrors which are incorporated in a set of vacuum tubes, in order to eliminate absorption on ambient water vapour. This involves transport of the radiation over a distance of several tens of meters (because the FEL is in a shielded area and the user stations are to be freely accessible), which puts stringent requirements on the stability of the transport system [15].

At the two facilities, research is being carried out in a variety of scientific disciplines: atomic physics, molecular physics/chemistry, solid-state physics, surface physics/chemistry (including interfaces), medicine, etc. [10, 16]. Both facilities are essentially open to the international community, but at CLIO there appears to be a somewhat larger contingent of local users than at FELIX. The latter facility serves groups from several member states of the EU, Russia, and the USA. In both facilities, beam time is allocated by an independent Programme Advisory Committee. Requests for beam time exceed the amount available typically by a factor of two.

In addition to short-term experiments with a 'mobile' set-up, several long-term projects are being carried out at the two facilities, with large (user-owned) equipment and frequent access to beam time. CLIO has permanent set-ups on near-field microscopy and sum-frequency generation at surfaces and interfaces. The latter involves nonlinear mixing of the FEL output with the output of a Nd:YAG laser on the surface in question. A similar set-up has been installed at FELIX, using a Nd:YLF laser. In the future, this laser will be available also for other two-colour experiments, such as pump-probe experiments. Furthermore, two cryogenic set-ups for research on semiconductors (for instance quantum wells) have been installed, and there are plans for installation of a pulsed 60-T magnet.

The user case is less evolved at the ENEA-FEL. In recent years, this machine was used mainly for basic FEL studies. However, exploratory user experiments have been carried out, for instance in the field of mm-wave detectors [17]. A first user station was furnished recently, and regular user operation is planned for mid-1995, with 500-1000 hours of beam time per year (depending on the available funding).

6. USER-ORIENTED UPGRADES

As mentioned above, a sizable fraction of the beam time is available for the execution of an in-house research programme on FEL physics at CLIO and FELIX. The objectives are similar, namely the implementation of upgrades and/or improvements of the performance that are relevant for users. There is some emphasis on the production of micropulses that are shorter and more intense than the - presently already very intense - pulses. This is important for studies of dynamic phenomenena having a short lifetime [7], for instance in semiconductor research, which is a large 'customer' at both facilities. The intrinsic FEL pulse length typically is of the order of the electron bunch length (a few ps) but this value can be changed roughly over an order of magnitude through a slight change of the length of the optical cavity [6]. At CLIO, dephasing the linac has resulted in the production of optical pulses as short as 500 fs, but the mechanism responsible for this is not yet understood [18].

When considering the FEL physics programmes, it is important to realize that the FEL is a regular laser in the sense that a stored wave is amplified on multiple passes through an optical cavity. This permits application of techniques that are customary in other lasers, such as the use of intracavity interferometric devices to control the linewidth (a technique which is being investigated at FELIX [8]) or cavity dumping to enhance the output power. In addition, however, an FEL is different from all other lasers in the sense that the properties of the laser medium - the electron beam - can be manipulated straightforwardly and on a fast timescale. For instance, the electron energy can be changed on a timescale down to the filling time of the linacs. With FELIX, such energy scans are made by ramping the bias voltage on the electron gun. This leads to a ramp in current which, behind the linac, is transformed into a ramp in energy (due to beam loading). As a result, the FEL wavelength is scanned by several per cent in a few μs. This kind of ultrafast scans could have important applications in, for instance, the photo-dissociation of molecules having an anharmonic energy level scheme.

7. CONCLUSIONS

Less than two decades after the first saturated FEL output was produced at Stanford, FEL technology in the infrared part of the spectrum has reached the level of maturity which is required for application in user experiments. Europe plays a prominent role in the exploitation of FEL user facilities, with fully operational facilities at Nieuwegein and Orsay, and possibly two or three more in the next years. The wavelength coverage of FELIX and CLIO together is unique on the global scene, and their pulse formats are complementary. User interest is overwhelming, illustrated by the fact that FELIX as well as CLIO is oversubscribed by a factor of two already.

8. REFERENCES

[1] W.B. Colson, C. Pellegrini, and A. Renieri, Laser Handbook Vol. 6, Amsterdam: Elsevier, 1990.

[2] D.A.G. Deacon, L.R. Elias, J.M.J. Madey, G.J. Ramian, H.A. Schwettman, and T.I. Smith, "First operation of a free-electron laser", Phys. Rev. Lett., Vol 38, pp. 892-894, 1977.

[3] G. Ramian, "The new UCSB free-electron lasers", Nucl. Instr. Meth. A, Vol. 318, pp. 225-229, 1992.

[4] G. Doucas, J.H. Mulvey, M. Omori, J. Walsh, and M.F. Kimmitt, "First observation of Smith-Purcell radiation from relativistic electrons", Phys. Rev. Lett., Vol. 69, pp. 1761-1764, 1992.

[5] T.I. Smith and H.A. Schwettman, "Facilities for using the FEL as a research tool", Nucl. Instr. Meth. A, Vol. 304, pp. 812-821, 1991.

[6] R.J. Bakker, D.A. Jaroszynski, A.F.G. van der Meer, D. Oepts, and P.W. van Amersfoort, "Short-pulse effects in a free-electron laser", accepted for publication in IEEE J. Quantum Electron.

[7] D.D. Dlott and M.D. Fayer, "Applications of infrared free-electron lasers: basic research on the dynamics of molecular systems", IEEE J. Quantum Electron., Vol. 27, pp. 2697-2713, 1991.

[8] D. Oepts, A.F.G. van der Meer, R.J. Bakker, and P.W. van Amersfoort, "Selection of single-mode radiation from a short-pulse free-electron laser", Phys. Rev. Lett., Vol. 70, pp. 3255-3258, 1993.

[9] C.A.J. van der Geer, R.J. Bakker, A.F.G. van der Meer, P.W. van Amersfoort, W.A. Gillespie, G. Saxon, and M.W. Poole, "A low-energy spread rf accelerator for a far-infrared free-electron laser", Nucl. Instr. Meth. A, Vol. 334, pp. 607-616, 1993.

[10] J.M. Ortega, "Operation of the CLIO infrared laser facility", Nucl. Instr. Meth., Vol. 341, pp. 138-141, 1994.

[11] R.J. Bakker, C.A.J. van der Geer, D.A. Jaroszynski, A.F.G. van der Meer, D. Oepts, and P.W. van Amersfoort, "Broad-band tunability of a far-infrared free-electron laser", J. Appl. Phys., Vol. 74, pp. 1501-1509, 1993.

[12] J. Auerhammer, H. Genz, H.D. Gräf, W. Grill, R. Hahn, A. Richter, V. Schlott, F. Thomas, J. Töpper, H. Weise, T. Wesp, and M. Wiencken, "First observation of spontaneous emission achieved with the Darmstadt IR-FEL", Nucl. Instr. Meth. A, Vol. 341, pp. 63-66, 1994.

[13] F. Ciocci, R. Bartolini, A. Doria, G.P. Gallerano, E. Giovenale, M.F. Kimmitt, G. Messina, and A. Renieri, "Operation of a compact free-electron laser in the millimeter-wave region with a bunched electron beam", Phys. Rev. Lett., Vol. 70, pp. 928-931, 1993.

[14] R.P. Walker, private communication.

[15] J.M. Berset, F. Glotin, D. Jaroszynski, J.M. Ortega, and R. Prazeres, "Optical alignment and beam extraction at the CLIO infrared laser facility", Nucl. Instr. Meth. A, Vol. 341, pp. ABS 29-30, 1994.

[16] A.F.G. van der Meer, R.J. Bakker, E.H. Haselhoff, D.A. Jaroszynski, G.M.H. Knippels, D. Oepts, and P.W. van Amersfoort, "Research with FELIX", Nucl. Instr. Meth. A, Vol. 314, pp. ABS 23, 1994.

[17] A. Doria, G.P. Gallerano, E. Giovenale, M.F. Kimmitt, and G. Messina, "Application of a millimetre-wave free-electron laser to study detection processes", Nucl. Instr. Meth. A, Vol. 341, pp. ABS 62-63, 1994.

[18] F. Glotin, R. Chaput, D. Jaroszynski, R. Prazeres, and J.M. Ortega, "Infrared subpicosecond laser pulses with a free-electron laser", Phys. Rev. Lett., Vol. 71, pp. 2587-2590, 1993.