LASING WITH FELIX

P.W. van Amersfoort, R.J. Bakker, C.A.J. van der Geer,
D.A. Jaroszynski, A.F.G. van der Meer, and D. Oepts
FOM-Instituut voor Plasmafysica 'Rijnhuizen', Nieuwegein, Nederland

Abstract

The Free Electron Laser for Infrared eXperiments (FELIX) has produced the first laser radiation in the summer of 1991. This made FELIX the first infrared FEL in Europe to come on the air. We report results obtained during the first half year of operation, such as measurements of the output power, tunability, the spectrum, and the stability, in relation with the performance of the electron accelerator.

1. INTRODUCTION

FELIX has been designed to constitute a rapidly tunable FEL user facility, initially operating in the spectral range from 8 to 80 μm [1]. The schematic layout of FELIX is given in Fig. 1. The electron accelerator consists of a 4-MeV injector (a thermionic gun operated at 1 GHz, a 1-GHz prebuncher, and a 3-GHz buncher), and two 3-GHz linacs. Laser radiation can be produced with two undulators, one operated at an electron energy of 15-25 MeV and one operated at 35-45 MeV. These undulators have been used earlier in the UK-FEL project [2]. The optical cavity in the low-energy beam line uses copper mirrors, with a central aperture of 3 mm diameter in the upstream mirror for coupling radiation out of the cavity.

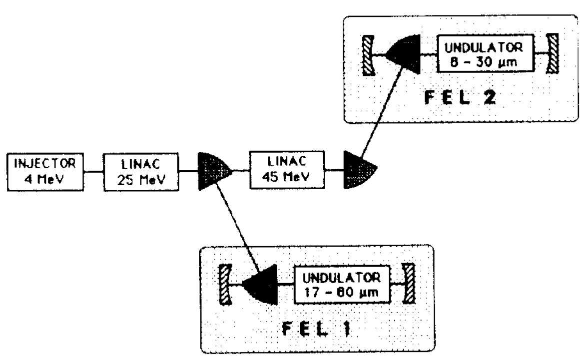

FIGURE 1. Schematic layout of FELIX, Stage I.

The performance of the electron accelerator is discussed in a separate contribution to this conference [3]. In brief summary, its characteristic features are as follows. The electron beam consists of a train of microbunches with a duration of a few ps and a charge up to 200 pC. The pulse-to-pulse spacing is 1 ns and, hence, the average current ranges up to 200 mA. The macropulse duration is 10-20 μs. The electron beam is bend into the optical cavity by means of a chicane of two 45° bending magnets and a quadrupole triplet to provide an achromatic (and reasonably isochronous) system. The beam is matched to the undulator field with an additional set of five quadrupole lenses.

The accelerator has been designed to produce an electron beam with an energy spread as small as possible. Also, a substantial effort has been made to provide optimum energy stability during the macropulse. This involves stabilization of the phase and amplitude of the 1-GHz rf signals to within 0.3° and 1%, respectively. The 3-GHz signals are stabilized to within 1° and 0.2%. The performance of the rf system is discussed elsewhere in these proceedings [4]. At present, of the order of 90% of the beam current is contained within an energy window of 0.4% [3].

2. TUNABILITY

One of the first saturated laser pulses, which was obtained in the summer of 1991, is presented in Fig. 2. The figure shows the electron current macropulse (12 μs, 200 mA) as measured on the beam dump behind the undulator, and the laser output. The micropulse structure cannot be seen in these oscilloscope traces, due to the limited bandwidth of the detectors used. The FEL output is seen to saturate roughly 9 μs after the start of the macropulse. Note that the output power is too small to be seen with the pyroelectric detector during the first 8 μs of the pulse, when the radiation intensity is building up from noise to the kW-level at saturation. The observation that the decay of the pyroelectric detector signal is delayed by roughly 1 μs with respect to the end of the current pulse is due to the fact that the detector response time and the cavity ring-down time are of the same order of magnitude.

After these first measurements, the stability of the rf system has been improved to meet the afore mentioned specifications. At present, saturation of the radiation intensity

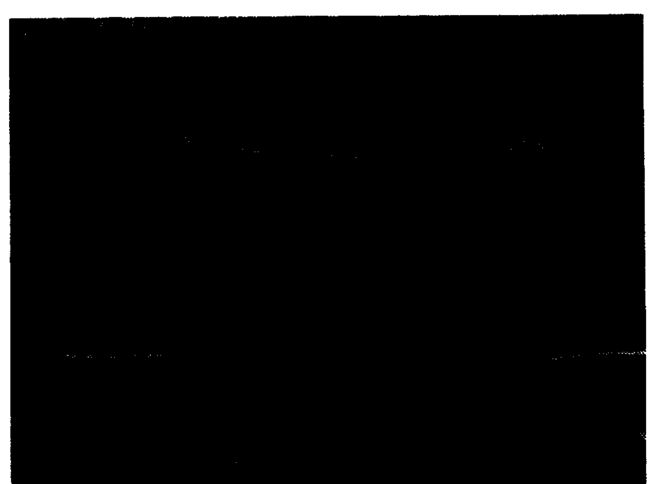

FIGURE 2. Saturated laser pulse (lower trace) and the current pulse (upper trace). A division along the horizontal axis corresponds to a period of 2 μs.

is obtained roughly 3-4 μs after the start of the electron macropulse, which indicates a single-pass FEL gain of the order of 50%. The saturated part of the pulse presently has a duration of 10 μs. Operation of FELIX is remarkably easy, and laser oscillation is usually obtained within less than ten minutes after start-up of the machine.

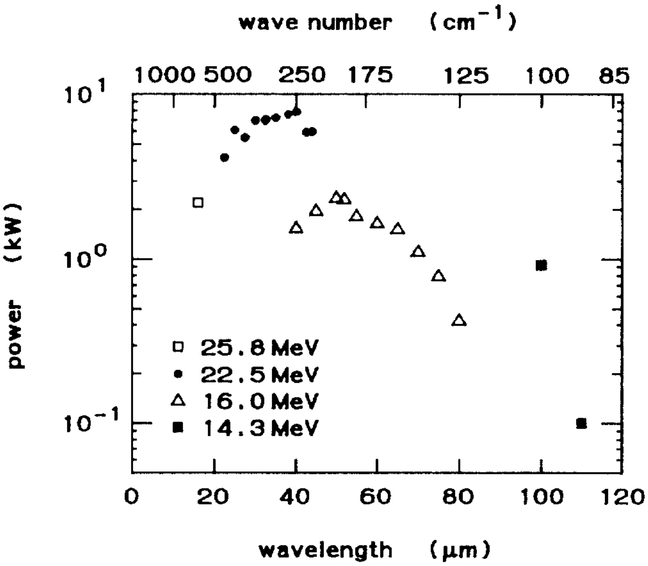

FIGURE 3. The average output power during the saturated part of the macropulse as a function of the radiation wavelength, for different electron energies. At a given energy, the wavelength is varied by variation of the undulator strength.

The saturated output power is shown in Fig. 3 for electron energies ranging from 14.3 MeV to 22.5 MeV and an rms undulator strength (a dimensionless parameter proportional to the undulator field) ranging from 0.5 to 1.2. It is seen that FELIX has produced a saturated output in the spectral range from 16 to 110 μm. At a fixed energy, the radiation wavelength can be scanned over a factor of two by variation of the gap between the two undulator halves, *i.e.*, the undulator strength. This is done by operation of a single knob, namely the knob that controls the motors used to adjust the gap. We have found that, at a large variation of the undulator strength, the electron beam is steered slightly off-axis, due to the fact that unavoidable errors in the undulator field change when changing the gap. Re-aligning the beam with the undulator axis, which is done with a set of steering coils placed in front of and alongside the undulator, and adjustment of the focussing quadrupoles for optimum overlap with the wave, improves the output power by roughly a factor of two.

The achieved wavelength coverage and the demonstration of single-knob tunability are 'firsts' in FEL research. The rapid tunability is a direct consequence of our decision, early in the design stage, to make wavelength scans primarily by variation of the undulator strength, rather than by variation of the electron energy. The latter would involve simultaneous adjustment of some 25 dipole and quadrupole magnets, focussing solenoids, steering coils, etc. In the future, users of FELIX will be given control of the tuning knob.

3. STABILITY

In first operation of FELIX we found that the current from the electron gun, a 100-kV triode, drooped by 4% during a macropulse of 30 μs duration. This was traced back to an amplitude droop of 3.7% at the output of the 1-GHz amplifier used to modulate the grid voltage [3]. This droop would lead to an energy ramp of some 300 keV behind the first linac (which corresponds to 1.2% at our maximum energy of 25 MeV), due to the fact that the beam-induced field in the linac changes when the current changes. In turn, this would cause the FEL wavelength to shift by roughly 2.4% during the

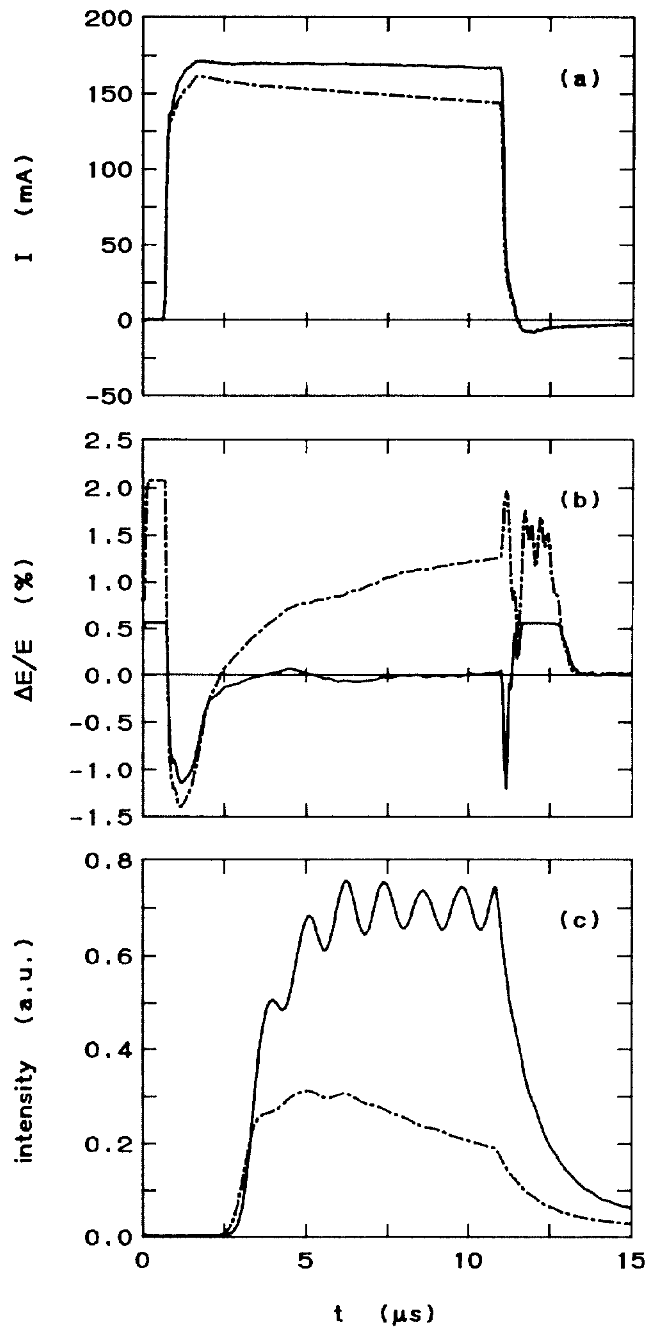

FIGURE 4. The influence of stabilization of the gun current. See text for details.

macropulse. This shift is of the same order of magnitude as the gain bandwidth and, hence, can be expected to strongly deteriorate the FEL performance. In view of this, we decided to compensate the droop by application of an appropriately ramped voltage to the grid (see Ref. 3).

Results obtained with our gun modulation technique are shown in Fig. 4, where we show (a) the current measured behind the first linac, (b) the beam position at a distance of 2 m behind the first bending magnet (as measured with a capacitive probe), converted to a deviation from the central energy, and (c) the laser ouput. The dashed lines give the uncompensated case and the full lines give the compensated case. It is seen that the intial energy ramp of some 1.2% during the last 9 μs of the pulse is reduced by an order of magnitude by our compensation technique. This improves the FEL output power by more than a factor of two.

In the compensated case, the saturated output power is seen to perform a limit-cycle oscillation. A detailed discussion of this effect is outside the scope of this paper, but we have strong indications that the oscillation reflects the formation of multiple subpulses in each optical micropulse. This new effect is a consequence of our combination of a long radiation wavelength and a short bunch length.

4. SPECTRAL MEASUREMENTS

The spectral width of the FEL radiation is determined to a large extent by the duration of the optical micropulses. In turn, the micropulse duration depends on the synchronism of electron bunches and circulating optical pulses, especially at our combination of a long radiation wavelength and a short bunch length. The synchronism is adjusted by variation of the length of the optical cavity. In a first set of measurements we found that the spectral width changes by at least a factor of ten (fwhm values range from 0.5 to 5%, at 42 μm wavelength) when the downstream mirror is scanned by a few wavelengths. In case of transform-limited operation, this would imply that the micropulse duration is adjustable from 3 to 30 ps.

The spectral stability is shown in Fig. 5a, for a central wavelength of 41.7 μm. It is seen that the wavelength is stable within 0.06%, which is at least an order of magnitude smaller than the width of the spectrum. This excellent stability is sufficient for all presently envisaged applications of FELIX. The deviation from the average electron energy during the macropulse, as determined with the capacitive probe mentioned above, is shown in Fig. 5b. The time dependence of this signal correlates nicely with the wavelength variation (an increase in wavelength coincides with a decrease in energy), which indicates that the residual energy unflatness causes the observed small wavelength variation.

5. FUTURE PLANS

All results presented in this paper were obtained with the undulator placed behind the first linac, in the period from August 1991 to January 1992. Meanwhile the second linac has been installed, and we are presently assembling the second beam line, which is expected to have been commissioned well

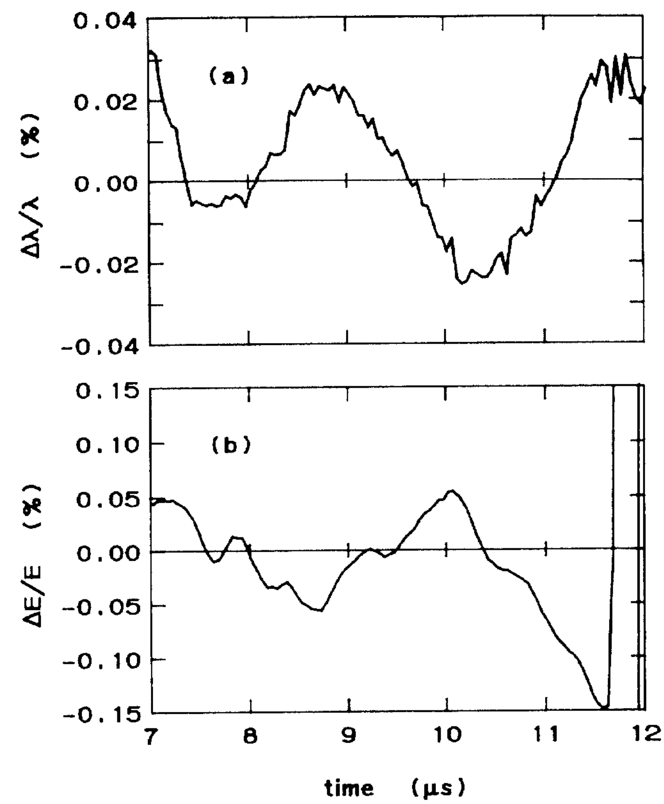

FIGURE 5. Spectral stability. See text for details.

before the summer of 1992. An evaluation of Stage I of the FELIX project by our funding agency, FOM, is scheduled to take place in August. After the budget for Stage II (which mainly involves user related equipment) has been released we will commence installation of the user facility. A number of exploratory user experiments have already been performed.

ACKNOWLEDGMENTS

This work was performed as part of the research programme of the association agreement between the *Stichting voor Fundamenteel Onderzoek der Materie* and EURATOM, with financial support from the *Nederlandse Organisatie voor Wetenschappelijk Onderzoek* and EURATOM.

REFERENCES

[1] P.W. van Amersfoort *et al.*, 'Update on FELIX', Nucl. Instr. Meth. A, vol. 304, pp. 163-167, 1991.

[2] C.R. Pidgeon *et al.*, 'The UK-FEL project: status and measurement of optical gain', Nucl. Instr. Meth. A, vol. 259, pp. 31-37, 1987.

[3] C.A.J. van der Geer *et al.*, 'Performance of the FELIX accelerator', these proceedings.

[4] P. Manintveld *et al.*, 'The FELIX rf system', these proceedings.

[5] D.A. Jaroszynski *et al.*, 'Consequences of short electron beam pulses in the FELIX project', Nucl. Instr. Meth. A, vol. 296, pp. 480-484, 1990.