START-UP AND RADIATION CHARACTERISTICS OF THE FELIX LONG-WAVELENGTH FEL IN THE VICINITY OF A TUNING GAP

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Abstract

Measurements of the small-signal gain, the cavity losses and the spectral characteristics of a partial-waveguide FEL in the vicinity of one of its prominent tuning 'gaps' are presented. A model is used to show that the observed reduction of the gain is due to mode conversion in the free-space part of the resonator in combination with a mode-dependent undulator gain.

INTRODUCTION

For FELs that operate in the far-IR, i.e. beyond 100 µm, the use of a waveguide in order to confine the optical mode, in particular inside the undulator, is highly advantageous. For a linearly polarized undulator, the preferred configuration consists of two parallel plates that compress the mode in the non-wiggling plane only. Inside such a waveguide, the eigenmodes are a combination of TE-modes (perpendicular to the plates) and Hermite-Gaussian modes (parallel to the plates)[1]:

$$\Psi_n(x,y,z)=\cos(\frac{nx\pi}{g})\exp(\frac{-y^2}{w^2(z)}+i(\frac{k_n^z y^2}{2R(z)}-\frac{1}{2}\tan^{-1}\frac{z}{z_r}))$$

with $k_n^z=\sqrt{k^2-n^2k_\perp^2}$, $R(z)=z+\frac{z_r^2}{z}$, $k_\perp=\frac{\pi}{g}$,

$z_r=\frac{w_o^2 k}{2}$, $k=\frac{2\pi}{\lambda}$ and $w(z)=\sqrt{1+\frac{z^2}{z_r^2}}\cdot w_0$ where w_0 is the waist of the beam in the wiggling plane, λ the wavelength in free space and g the distance between the plates. Here x and y are chosen perpendicular, resp. parallel to the plates and z points along the resonator axis. The modes with odd *n* have a maximum on axis and will therefore have stronger coupling to the electron beam. The phase velocity of the modes increases with *n*, causing a down shift of the FEL resonance frequency that increases with *n*. The group velocity decreases with increasing *n* resulting in a decrease of the optimal cavity length in the case of a bunched electron beam.

In case the polarization of the undulator radiation is parallel to the plane of injection and extraction for the e-beam, the beam can enter and leave the waveguide without having to cross the waveguide walls. In that case the waveguide can extend all the way from the upstream mirror of the resonator to the downstream mirror, as is e.g. the case for the FEL at UCSB. Because the polarization of the exisiting undulator for the long-wavelength FEL (FEL-1) at the FELIX facility was perpendicular to the injection plane, it was decided to start the waveguide, needed to increase its long-wavelength limit from 100 to 250 µm, only after the injection dipole. Presently two other FELs make use of a partial waveguide: CLIO [2] in Paris and the long-wavelength branch of FELBE [3] in Rossendorf. An unexpected and rather annoying feature of the performance of these FELs is the occurrence of pronounced tuning "gaps": narrow spectral regions where the output is strongly reduced or where the laser even fails to start up. These "gaps" are clearly visible in a typical power curve of the FELIX FEL-1 when tuned over the spectral range from 30 to 70 µm (see fig. 1). Although details of the curve depend on machine settings, the positions of the "gaps" are very robust.

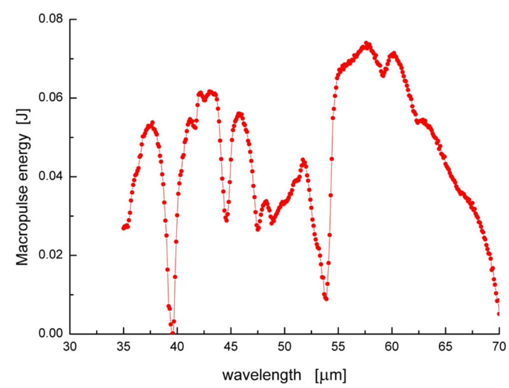

Figure 1: Typical macropulse energy of FEL-1 when tuned from 35 – 70 µm for the top mirror of fig 2.

CHARACTERISTICS OF FEL-1

FEL-1 was designed to cover the spectral range from 30 to 250 µm [4]. The undulator has 38 periods of 65 mm and the polarization is vertical. At a minimum gap of 22 mm, the K_{rms}-value is 1.8, giving a lowest beam energy requirement of 12 MeV. The length of the resonator is 6 m while the length of the waveguide is 4.34 m. The distance between the waveguide plates is 10 mm and so the relative shifts in resonance frequency are of the order 10^{-2} n^2 λ %, with λ in µm. The downstream mirror, positioned between the plates, is cylindrical, with a radius of curvature in the vertical (y) plane of 4 m. Whereas the wavefront of the optical beam in between the waveguide and the upstream mirror forms a circle in the y-z plane, it deviates somewhat from a circle in the horizontal (x-z) plane. Moreover, the curvature in this direction is wavelength dependent. The spotsize on the mirror increases with wavelength, but with different rates: the rate in the horizontal plane is faster than in the vertical plane. To accommodate this wavelength dependence, five toroidal mirrors each with a different

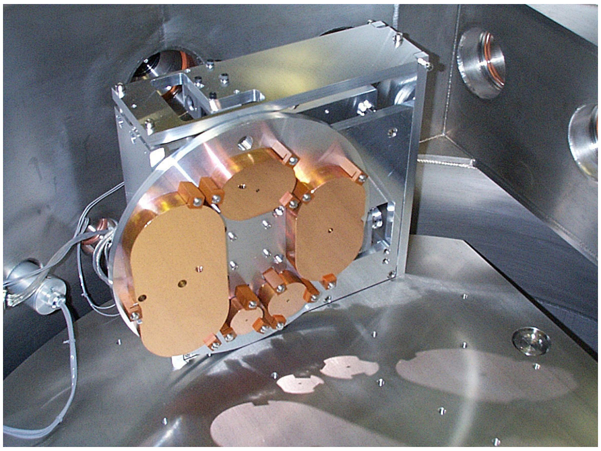

Figure 2: Photograph of the mirror carousel. The mirror at the top is on the resonator axis.

curvature, shape and size, are fitted in a carousel to cover the 30 – 250 µm spectral range. A photograph of the carousel is shown in fig. 2. The radii in the vertical plane are all equal to 4 m, whereas the radii in the horizontal plane vary from 2500 mm for the smallest mirror to 1660 mm for the largest mirror. The diameters of the holes used for outcoupling vary from 1.6 to 7 mm. As a result of the outcoupling hole and the residual mismatch between the mirror curvature and the curvature of the optical beam, some coupling between odd modes with different n will occur (and similarly for the even modes). An example is shown in fig. 3 for the second but smallest mirror. The power loss of the lowest order (n = 1) transverse mode due to outcoupling, diffraction and mode conversion on reflection from the mirror and coupling into the waveguide, starting with a pure n = 1 mode at the waveguide exit, is shown as a function of wavelength.

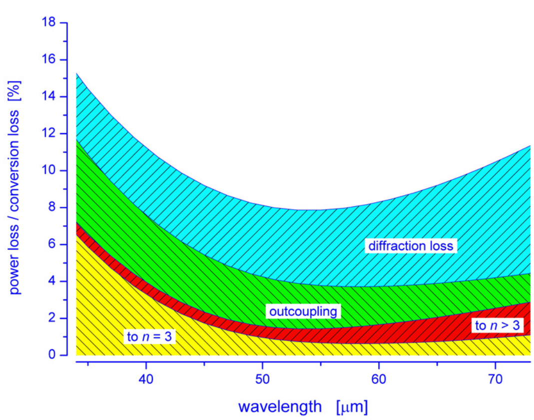

Figure 3: Conversion loss for the n = 1 mode in the free-space part, starting with a pure n = 1 at the waveguide exit.

The primary loss channels at short wavelengths are mode conversion to n = 3 and outcoupling, whereas at long wavelengths the diffraction loss dominates [5], primarily due to inefficient coupling into the waveguide. From the tuning curve presented in fig 1, it is clear that FEL-1 exhibits several 'spectral 'gaps' in the 30 – 70 µm range. For the other mirrors and at longer wavelengths the 'gaps' are also rather abundant. For the remaining part we will focus on the 'gap' around 38 µm. Partly because experiments become increasingly more difficult at longer wavelengths, partly because it is one of the very persistent 'gaps' where it is virtually impossible to make the laser reach saturation within the 10 µs duration of our macropulse. Fig. 4a shows a measurement of the small-signal gain and the cavity loss, derived from the ring-down of the cavity, in the vicinity of this gap, while in fig. 4b the average wavelength and the spectral width are shown versus

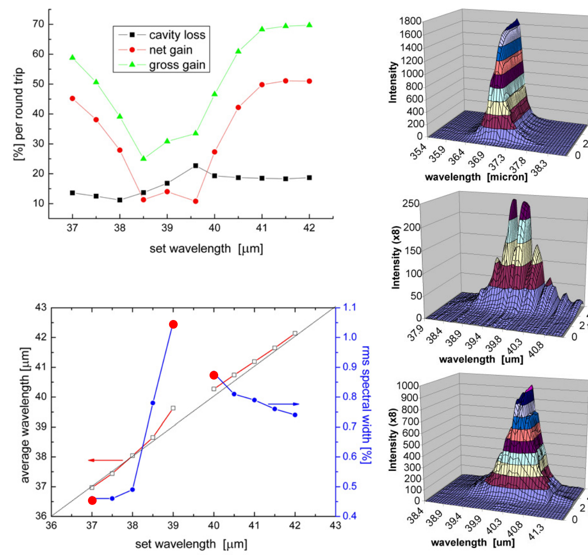

Figure 4: Measured small-signal gain and cavity losses (a, top left), average wavelength and spectral width (b, bottom left) and (c, right) spectral evolution for the red dots of panel (b).

the wavelength computed from the beam energy and undulator gap settings. In fig. 4c the time evolution of the spectrum is shown for the three red dots of panel b.

A number of observations can be made from these measurements: (i) the gain is strongly reduced in the 'gap', (ii) the cavity loss increases when crossing the 'gap' from shorter to longer wavelength and (iii) the spectrum tends to shift to longer wavelength while at the same time the spectral width increases.

As it was suspected that mode competition between modes with different n plays an important role, a slit parallel to the waveguide plates was installed in front of the upstream mirror to act as a crude spatial mode filter. Reducing the effective mirror size in this direction from 38 to only 15 mm, the laser did reach saturation well before the end of the macropulse. For this case a similar set of measurements as fig. 4 are shown in fig 5. As was to be expected, the cavity loss is now much higher, but still the net gain has increased and the sum of the two, indicative of the FEL gain, does not show any sign of the presence of a tuning 'gap'. From an operational point of view the use of a slit is no solution, though, because the output power is low due to the unfavourable ratio between outcoupling and diffraction loss. The high losses also severely limit the flexibility in setting the spectral width by means of the cavity length detuning in that case.

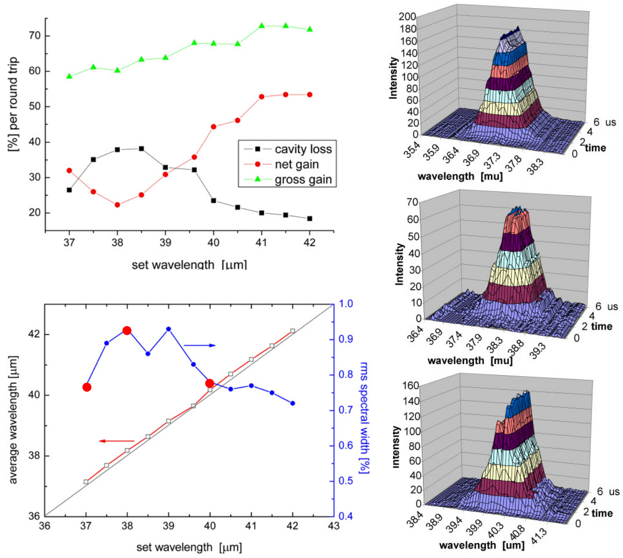

Figure 5: As fig 4. but now with a 15 mm slit in front of the 38 mm-size mirror.

MODELLING

In a recent paper [6], the operation of FELs with a partial waveguide and hole coupling was simulated by means of an iterative algorithm to find an equilibrium optical mode pattern that was used to compute the cavity loss and the outcoupled power. Spectral 'gaps' were indeed found and the agreement with experimental tuning curves for both CLIO and FEL-1 was quite satisfactory. From these simulations it was concluded that the 'gaps' are caused by a sudden change in the mode pattern. At the short wavelength side only the n = 1 mode is present, resulting in low cavity loss and decent outcoupling. In the spectral gap, higher order modes are present that cause a local minimum of the power on the mirror at the position of the hole resulting in very low outcoupling. Beyond the gap, higher order modes are also present but now the outcoupling is actually rather high and so are the cavity losses, mainly occurring at the waveguide entrance, resulting in a low intracavity power. Especially this latter case is surprising: why does the laser prefer a mode pattern with high losses and low intracavity power? Another important observation made in [6] was that the spectral distance between the 'gaps' found in the simulations could be calculated using the requirement that the phase advance of the n = 3 mode relative to the n = 1 increases by 2π [7]. Being an algorithm to compute the equilibrium mode pattern, it could not provide insight in the experimentally observed start-up problem. In fact, from the equilibrium found, it was not apparent that there could be a start-up problem. A limitation of the algorithm is that it uses a single frequency, whereas the FEL resonance frequency is different for different n. For the parameters of FEL-1, the n = 3 mode can even be attenuated instead of amplified by the interaction with the electron beam at the resonance frequency of the n = 1 mode. Finally, only the mode profile at the centre of the undulator is used to compute the gain, whereas in reality the profile will change along the waveguide as a result of the difference in phase and group velocities of the modes with different n.

To address the start-up phase, we developed a time-dependent model that can handle short pulses and frequency dependent gain. The model is based on a local, numerical evaluation of the low-gain, small-signal FEL equation along the undulator and across the electron beam profile. The FFT scheme developed by Prazeres [8] is used for the propagation of the field, both in the waveguide and in the free-space region. The bandwidth is sufficient to take the shifts in resonance frequencies for the n = 3 and n = 5 modes, relative to that of n = 1 at 38 μm, properly into account. For simplicity, the dependence in the y-direction, i.e. parallel to the waveguide plates, is ignored, with as main consequence that the effect of the outcoupling hole is neglected. Some results produced with this algorithm using input parameters characteristic for FEL-1 and a pure n = 1 mode short pulse as seed [9], are shown in fig. 6.

As can be seen, the model indeed predicts a narrow range of wavelengths where the intensity build-up is frustrated. From fig. 6b it follows that the drop in gain coincides with an increase of the fraction of the power present in the n = 3 mode, which can reach values well above 50%. The frequency of this n = 3 mode is found to be the same as that of the n = 1 mode, which means that it is not at the frequency required for FEL gain, but rather at a frequency where it is attenuated. It must therefore be produced from the n = 1 mode. Given the conversion rate from n = 1 to n = 3 from the exit of the waveguide to the input of some 4% (see fig. 3), this may seem somewhat surprising. The explanation becomes evident when looking at the mode evolution in the empty cavity, so without electron beam (see fig. 7). It shows an oscillation of the power flowing from n = 1 to n = 3, with a resonance at a wavelength that is slightly shifted to longer wavelengths [10]. The oscillation is damped as a result of the roundtrip losses, including a 4% loss to account for reflection- and outcoupling loss. This oscillation is caused by the dependence of the conversion loss from n = 1 to n = 3 on the presence and relative phase shift of n = 3 at the exit of the waveguide, which is also illustrated in fig 8.

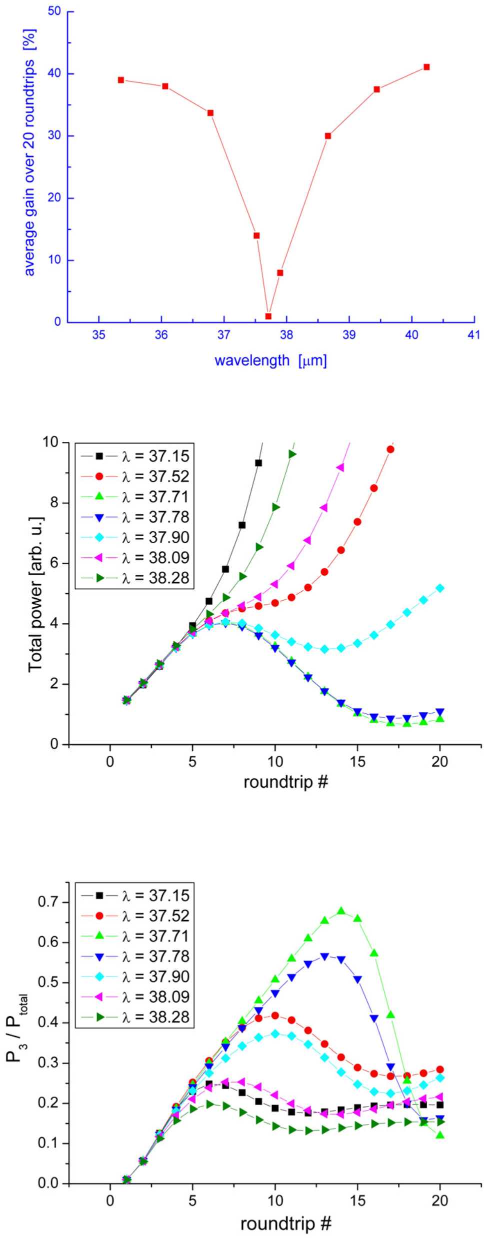

Figure 6: Computed average gain over the first 20 roundtrips (top), the evolution of the total power near the 'gap' (middle) and the relative power in the n = 3 mode (bottom).

So the primary reason for the failure to start-up at 37.7 μm is that the loss of the n = 1 by mode conversion becomes too large to be compensated by the gain while at the same time the n = 3 mode will not sufficiently convert back to n = 1 as it is suffering from attenuation by the FEL interaction. This is not the complete picture, though, as follows from fig. 9 where the simulation results at this wavelength are shown for different positions of the undulator relative to the waveguide entrance. From these results, it follows that the relative phase of the modes also influences the gain in the undulator. This is caused by the dependence of the overlap between optical mode profile and electron beam profile on this relative phase.

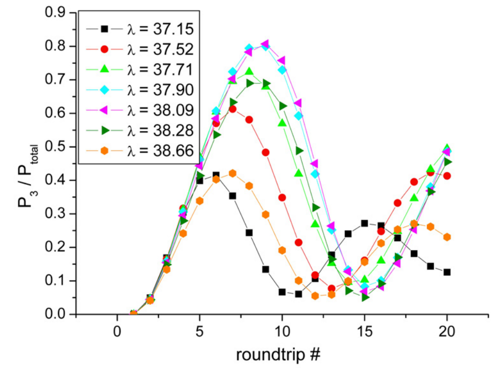

Figure 7: As fig. 6c but without electron beam.

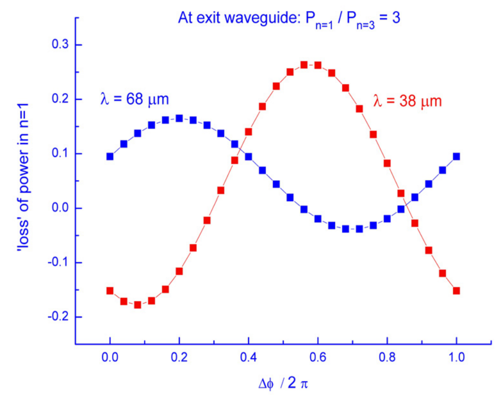

Figure 8: Conversion loss from n = 1 to n = 3, starting with 25% of the power in the n = 3 mode at the exit of the waveguide, as a function of the relative phase.

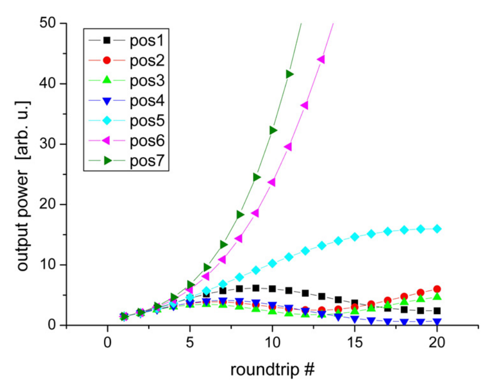

Figure 9: Dependence of the start-up at λ = 37.7 μm on the position of the undulator. Position 4 corresponds to the actual position. (The steps in position are 300 mm).

CONCLUSIONS

The start-up problems observed in FELs with a partial waveguide resonator are most likely caused by the coupling, induced by the waveguide to free space to waveguide transition, between the n = 1 mode and the higher order transverse modes of the same frequency [11]. This coupling is particularly strong at wavelengths where the roundtrip relative phase shifts of the modes is close to an integer times 2π. As the dominant higher order mode, n = 3, at the frequency of the lowest order mode, is not amplified but rather attenuated, this will drain the power of the n = 1. Depending on the relative phase of these modes in the undulator, this can reduce the roundtrip gain of the n = 1 mode to a level that prevents a build-up to saturation within the macropulse of the electron beam.

At saturation this coupling remains, and is the reason for the relatively large higher order transverse mode content that can result in low outcoupling and/or high cavity losses, as was shown in [6].

The n = 3 mode at a frequency that could be amplified by the FEL interaction also plays no role in our case, as the roundtrip losses exceed the FEL gain for this mode. In view of this, it is no longer surprising that, apart from the start-up issues, the single-frequency simulations of [6] reproduce the experimental findings rather well.

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[10] This small shift is due to the difference in electron-beam-induced phase shifts for the n =1 and n =3 modes.

[11] In contrast with the suggestion in [12] that phase differences between the higher order modes generated by the electron beam are the primary cause.

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