SATURATION DYNAMICS, FINE SPECTRUM, AND CHIRP CONTROL IN A CW FEL OSCILLATOR

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Abstract

Here we report in brief the results of an experimental study of the saturation dynamics and the optimal conditions for maximal radiation power extraction in a Free Electron Laser (FEL) oscillator. The Israeli Electrostatic Accelerator Free Electron Laser (EA-FEL) is capable of providing lasing pulses at frequencies between 95-110 GHz (depending on the electron beam energy). A critical parameter affecting the performance of the laser is the reflectivity and transmission of the out-coupling element of the resonator.

By attaching a variable reflectivity out-coupling element (based on a series of wire-grid polarisers) to the resonator of our EA-FEL we demonstrate the ability to optimise performance depending upon the desired output. For maximum lasing time the out-coupling from the resonator must be minimized, although sufficient for some radiation to leave. For maximum peak-power the reflectivity must be set differently depending upon the energy of the electron-beam (in MeV), which relates to the frequency emitted, and to the magnitude of the electron-beam current (in A). Mode competition ceases and a single longitudinal resonator mode is established more quickly the higher the reflectivity (important for short pulses).

The variable out-coupling allows us to operate optimally over a large range of frequencies and beam currents which would be impossible with an element with fixed reflectivity.

INTRODUCTION

Most FELs are based on RF-Linac acceleration technology that provides a periodic train of picosecond range e-beam pulses. FEL oscillators constructed based on such accelerators operate in principle as analogues of conventional mode-locked lasers [1]. In such oscillators, the laser radiation pulses are a superposition of numerous longitudinal modes of the resonator. By contrast, FEL oscillators based on electrostatic acceleration, which are the focus of the current article, can operate in a quasi-CW mode, namely their pulse duration is much longer than the time for several photon round-trips in the resonator. Such FEL oscillators operate analogously to conventional CW lasers of homogenously broadened gain medium.

Consequently, they can operate at a single longitudinal radiation mode, and the physics of their steady state saturation and output coupling power optimization can be analysed in terms of conventional laser theory. Though there are many FEL oscillators operating in the world [2], there are few operating electrostatic accelerator FELs in which the laser oscillator physics and specifically the problem of power out-coupling optimization can be studied experimentally. The Israeli Electrostatic Accelerator FEL (EA-FEL) is one of them. Another is the UCSB FEL [3]. Both can operate in a quasi-CW mode. The Dutch FOM-FEL operated along similar principles and at higher power but has since been dismantled [4]. An EA-FEL has also been built in Korea [5]. The Israeli Tandem EA-FEL has at its heart a fixed linearly polarised Halbach Wiggler [6].

POWER OUT-COUPLING OPTIMISATION

The subject of optimal power outcoupling for attaining maximum lasing power output is treated by most standard texts on lasers [7-10]. This same subject of optimal power outcoupling in EA-FEL has not been studied extensively so far. The Israeli FEL group experimented with optimisation of power outcoupling of an FEM operating at microwave frequencies [11]. The matter was also treated by us theoretically in relation to our Tandem EA-FEL, which is the subject of this paper [12].

Table 1: General System Parameters of the EA-FEL

Beam Current	0.5-3 A
B_w(Wiggler Field Amplitude)	0.193 T
λ_w	44.4 mm
A_e (Effective area of mode)	$40.1 \times 10^{-6}\ m^2$
L_w – Wiggler Length	989 mm
Beam Kinetic Energy	1.4 MeV

Within the limitations of our measurement range, single mode operation is generally observed. The time for single mode operation depends upon the roundtrip reflectivity. We arrive at this conclusion from looking at the lasing spectra, which we obtain from heterodyne mixing of the attenuated laser signal. We use an oscilloscope with a sampling rate of 5 GHz (Agilent – DSO-X3104A), with an analog bandwidth of 1 GHz. In producing the output the mixer doesn't discriminate between lasing frequencies above or below the local oscillator; so the 1 GHz bandwidth of the oscilloscope shows scanning over a range of over 2 GHz (±1 GHz from the local oscillator). So any demonstration of single mode operation is limited to 2 GHz. Though, the gain bandwidth of lasing is also limited, lasing further from the

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maximal gain point is less likely to survive the mode competition.

In Fig. 1 and 2 the spectra produced by the mixer are shown. The first time windows of the spectra in these figures are presented from the moment build-up begins, not from the time the electron beam starts! That is, depending upon the reflectivity there is a period of between 0.5 to 2.5 μs before there is any measurable lasing occurring.

In Fig. 1, it appears single mode operation is established after the second time window, between 1.5-2.5 μs. For the case shown in Fig. 1 the reflectivity of the out-coupling element was set to 0.89. By contrast, in Fig. 2, where the reflectivity of the out-coupling element was set to just 0.81, the mode competition is still evident in the third time window. Single mode operation is attained only after another 0.7 μs, where the two small satellite modes in the third frame disappear (not shown). For both Figs 1 and 2 the beam energy was ~1.36 MeV, the beam current 1.3 A, the lasing at frequencies close to 96.4 GHz and the internal losses of the resonator ~0.65 (at this frequency). During these pulses the accelerating voltage was falling at ~0.7kV/μs.

We expect that the gain curve will shift nearly linearly with the accelerator terminal voltage. This was found to be for the parameters of the EA-FEL [13] $\Delta f_{max}/\Delta V = 166\ MHz/kV$, due to a given drop in voltage ΔV over time t. When the voltage drop was $\Delta V/\Delta t \sim -0.5kV/\mu s$, this meant a change in the central frequency of the gain curve of $\Delta f_{max}/\Delta t = 83.05$ MHz/μs. So for a FWHM net-gain bandwidth of 5 GHz the gain curve needs to shift by roughly 2.5 GHz for lasing to cease, this should take ~2.5/0.08305 = 30.1 μs (assuming the dominant mode is built up at a frequency close to the maximum gain frequency). Although due to frequency pulling, despite the large shift in the gain curve, the lasing frequency will only change by ~5 MHz.

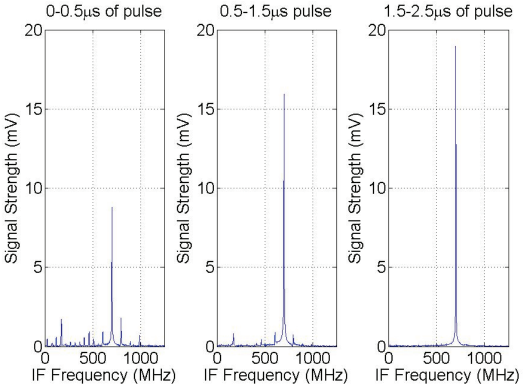

Figure 1: With the out-coupling element set to a reflectivity of 0.89 we observe the development of the lasing over three time windows. The lasing is 701 MHz above the LO which was set to 95.7 GHz. It appears that by the period of the final time window single mode lasing is established.

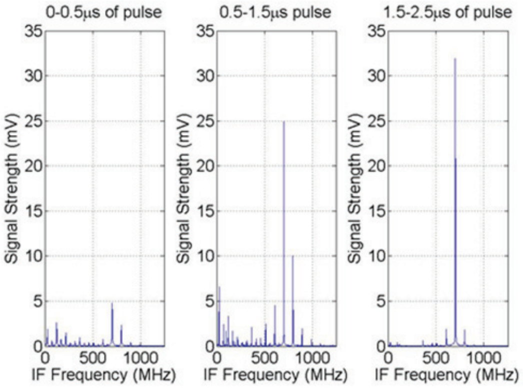

Figure 2: With the out-coupling element set to a reflectivity of 0.81 we observe the development of the lasing over three time windows. The lasing is 702 MHz above the LO which was set to 95.7 GHz. It appears that by the period of the final time window single mode lasing is not yet established.

LASER OUTPUT POWER OPTIMISATION

Earlier we considered how changing the out-coupling of the resonator changes the parameters of the lasing. Now we present measurements, which are compared to simulations, of the results of lasing power output as a function of out-coupling. We present this for a beam energy of ~1.36 MeV which corresponds to a frequency of 96.4 GHz, whilst the beam current was 1.3A (see Fig. 3). The variability from pulse to pulse is not due to uncertainty in the measurement but instability in the accelerating potential. Remarkably, this beam energy fluctuation having little effect on the small signal gain, often did not cause change from pulse to pulse in the lasing frequency, but dispersed the saturation power output. The simulated curves were produced in FEL3D [14].

Noting that the lasing ceases below a reflectivity of ~0.784 whilst the internal losses in the resonator at 96.4 GHz are ~0.65 we calculate the gain to be G=3.64.

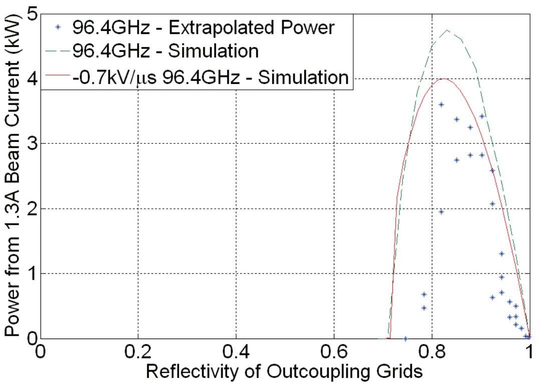

Figure 3: Power as a function of resonator exit reflectivity at 96.4 GHz, extrapolated from measurements in the user room to the output of the resonator.

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CONCLUSION

The optimisation of power output from a free electron laser oscillator based on an electrostatic accelerator has been demonstrated and the effect of voltage fluctuations on the saturation power observed. This optimal coupling point was achieved experimentally by remote-control tuning of the transmission of a variable reflection mm-wave mirror at the end of the resonator. FEL3D simulations of output power maximisation and oscillation build-up and saturation were consistent with the experimental conclusions. We demonstrated FEL oscillation build-up and establishment of narrow bandwidth single mode operation within a few microseconds. A more expanded version of this text is to be published shortly in IEEE MTT.

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