ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUC04

ENHANCEMENT OF RADIATIVE ENERGY EXTRACTION IN AN FEL OSCILLATOR BY POST-SATURATION BEAM ENERGY RAMPING

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Abstract

We present results of experiments and simulations showing a greater than 50% increase in post-saturation radiation power extraction from a Free Electron Laser oscillator based on an electrostatic accelerator. Electrostatic accelerator free electron laser oscillators have the potential for CW operation. Present day operating oscillators rely on long pulses of electrons, tens of microseconds in duration, they generate correspondingly long radiation pulses, at a single longitudinal mode after a mode competition process. The post-saturation power extraction enhancement process is based on temporal tapering (up-ramping) of the beam energy, enabling a large synchrotron oscillation swing of the trapped electron bunches in passage along the interaction length. We further discuss the theoretical limits of the temporal tapering efficiency enhancement process.

INTRODUCTION

Of the FEL oscillators operating in the world [1], few operate with an electrostatic accelerator [2-6], one of them is the Israeli Electrostatic Accelerator FEL (EA-FEL). Generally, in FEL only a small proportion of the electron kinetic energy is extracted in the form of radiation. One way of increasing the efficiency of extraction is use of a tapered wiggler. That is, when the undulator period and or magnetic field are modified [7-10]. This ensures that as electrons lose kinetic energy their interaction with the radiated electric field remains strong [11]. Spatial undulator tapering has been proved already in experiments with an amplifier FEL [12-13]. All these works are connected to single-pass Self-Amplified Spontaneous Emission (SASE) amplifier FELs.

Oscillator FELs are multi-pass radiation systems. The out-coupling of the resonator can be modified until the optimum energy balance with the resonator internal losses is found for maximum radiative output power [14]. Pre-bunching the electron beam has also been shown to increase the extraction efficiency of radiative power [15].

Another way to increase the extraction of useful radiative energy is to positively-ramp the kinetic energy of the electron beam entering the resonator post-saturation. This temporal tapering of the electron parameters serves to raise the electrons, in terms of their potential to radiate, onto a more energetically favourable synchrotron oscillation path. Such a scheme was demonstrated via experiment and simulation for the first time [16].

Figure 1 shows a schematic of the Israeli Tandem EA-FEL. A thermionic cathode e-gun is biased to -40 kV and provides electron beam pulses with currents in the range 0.7-3 A and up to 100-µs duration. These electron beam pulses are accelerated up to around 1.4 MeV where they enter an equipotential region where they are focused by quadrupoles for optimal entrance into the resonator (which is encompassed by a planar Halbach wiggler [17]). After passing through the resonator the electrons are again focused by quadrupoles before entry into the deceleration tube, at the end of the deceleration tube they are collected. Under regular operation the resonator and wiggler are at the same potential as the sections with the quadrupoles between the acceleration and deceleration tubes. The main properties of the EA-FEL are summarised in Table 1, and described in a previous publication [14].

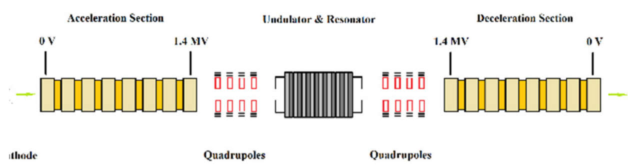

Figure 1: Schematic of the Israeli EA-FEL based on a Tandem Van-der-Graaf generator.

Table 1: Properties of the EA-FEL

Beam Current	0.7-3 A
Beam Energy	1.35-1.45 MeV
Wiggler Period	44.4 mm
Effective No. of Wiggler Periods	24
Wiggler field Amplitude	1.93 kG
Waveguide Fundamental Mode	HE11
Radiation Frequency	95-110 GHz
Optical Length of Resonator	1.514 m
Free Spectral Range of Resonator	100 MHz

A voltage ramping device (VRD) was built to compensate for falling accelerating voltage due to electrons hitting the walls of the beam line. The VRD is an electronic circuit composed of a 20-kV bipolar power supply that is remotely triggered to charge a capacitive load through selectable resistors producing an exponential pulse of rise time $\tau = RC$ that is nearly linear for time $t < \tau$. The first purpose of the

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device was to stabilise the lasing frequency and increase lasing time with its use. The VRD is connected directly between the electrically short-circuited resonator and undulator and the high voltage terminal metallic baseplate. The undulator sits on ceramic mounts to isolate it from the high voltage equipotential region of the terminal. The isolated resonator/wiggler acts as one surface of a capacitor and is charged by the VRD synchronously with the start of the electron-beam from the cathode. The charging rate is controlled through different resistors. As the resonator is isolated from the high voltage terminal, voltage ramping relative to the terminal increases the kinetic energy of the electrons upon entry to the wiggler to compensate or over-compensate the potential energy drop of the terminal.

INCREASING EXTRACTION FROM THE ELECTRON BEAM

As we do not have precise control over the accelerating voltage due to the inherently limited pulse to pulse voltage stability of the electrostatic accelerator, there is some variability from pulse to pulse in the radiation output power. However, by comparing the output power data of a series of pulses it is possible to see the effect of voltage ramping on the peak output power from the resonator. Three cases were tested in a series of 75 lasing shots (see Fig. 2). During this entire series of experiments the accelerating voltage was dropping by 2.26 kV/μs during each pulse. The distribution of the first 25 lasing shots of Fig. 2, marked as stars were without voltage ramping. Then 25 lasing pulses with 20 kV voltage ramping and τ = 8 μs are marked with diamonds, and finally another 25 lasing pulses with 20 kV voltage ramping and a rise time of τ = 2 μs are marked with circles. The average peak power for each of the three cases is marked on the graph with a horizontal bar. From left to right in Fig. 2 the averages are 1690 W, 2260 W, and 2505 W. It is seen that the average peak power of the τ = 2 μs case was on average 50% higher than without. Even though the same electron beam current of 1.13 A was being used in all cases. The transmission of the resonator output was ~5%.

The rate of increase in voltage in the two cases is only a factor because the ramping is counteracting the falling accelerating potential and there is an optimal increment above the initial beam energy. So, in the case of τ = 8 μs the beam energy increment is just compensating for the voltage drop, when the rate of ramping is increased to τ = 2 μs the beam energy rises above the beam energy that corresponds to the maximum of the small signal gain, this results in a significantly increased extraction efficiency. This increase is the main point of interest. It means that post-laser-saturation, the maximum gain point is shifted from the point before the build-up process. The experiment described just checked two very limited cases with fixed resonator transmission.

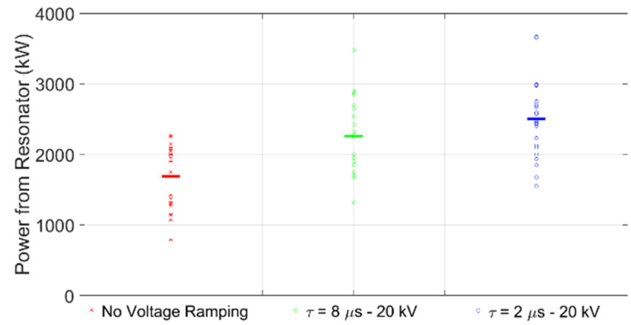

Figure 2: Summary of the results of the initial peak power obtained from 75 lasing pulses. Of the 75, 25 were carried out without voltage ramping (leftmost stars), 25 with a compensating voltage ramping pulse of rise time τ = 8 μs - centre diamonds), and 25 with an overcompensating pulse of rise time τ = 2 μs - rightmost circles. The averages of the markers are shown with a horizontal marker.

FINDING THE MAXIMUM ENHANCEMENT FROM BEAM ENERGY RAMPING

To simulate the effect of falling or rising beam energy, the electron-radiation interaction dynamics code FEL3D was used. The simulation code is a steady state, single frequency, and single pass (amplifier) program, considering three-dimensional effects due to a finite beam size and a non-uniform profile of the undulator magnetic field.

The results of the FEL3D simulation of extracted power for a given beam energy ramp with a 1.13-A current (and the parameters in Table 1) are depicted in three sets of graphs in Fig. 3. We demonstrate the effect of voltage ramping here at three different ramping levels, 0 kV (top), 10 kV (graph), and 20 kV (bottom), for roundtrip reflectivity levels of 0.35, 0.45, 0.55, and 0.61. The initial beam energy in each of the graphs is that for the maximum of the small signal gain at the frequency oscillating in the resonator. The top graph is the power developed in the resonator with no change in beam energy. The middle graph shows the effect of an abrupt 10-keV increment in the beam energy.

It is interesting to note that the increase in resonator power is not uniform for different levels of roundtrip reflectivity. Indeed, in the bottom graph, whilst a 20-kV ramp causes a 60% increase in power for R_{rt} = 0.61, for R_{rt} = 0.35, this causes an end to lasing. For R_{rt} = 0.61 there is more stored power in the resonator than for R_{rt} = 0.35, so when the beam energy is raised 20 keV, for the R_{rt} = 0.61 case the electrons are moved to a more favourable synchrotron oscillation trajectory from the point of view of energy extraction, whereas for R_{rt} = 0.35 the electrons become detrapped (for a more detailed discussion, see [16]).

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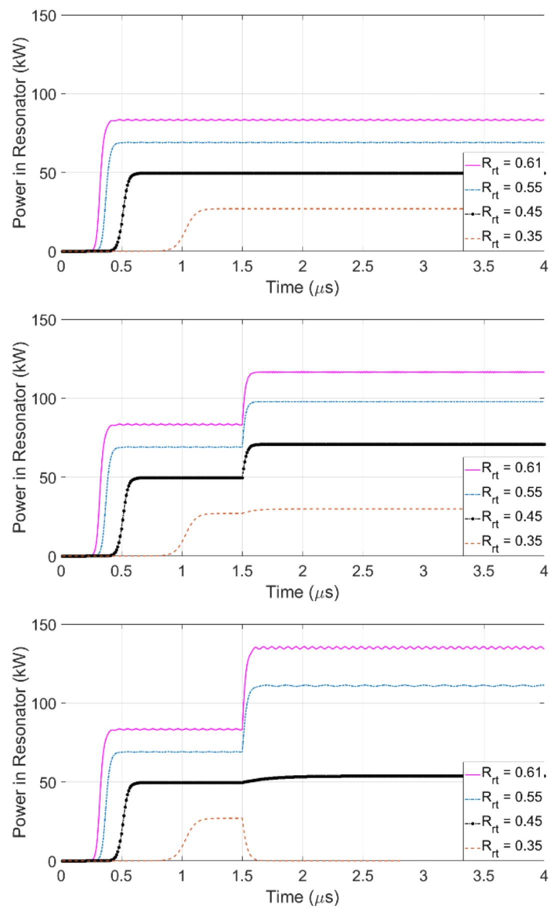

Figure 3: Power stored in the resonator as a function of time. The beam energy is that for maximum small signal gain. No change is made to the beam energy in the top graph. In the middle and bottom graphs an abrupt increase of 10 and 20 keV respectively is made at 1.5 µs.

CONCLUSION

Via simulation and experiment, the importance of post-saturation changes in electron beam energy to output power has been demonstrated. This is the first experimental demonstration for an FEL oscillator of efficiency enhancement of energy extraction from an un-bunched continuous electron beam using voltage ramping where 50% more radiation power has been obtained.

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