HIGH POWER COUPLED FEL OSCILLATORS FOR THE GENERATION OF HIGH REPETITION RATE ULTRASHORT MID-IR PULSES

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Abstract

100-200 MeV range ERL driven high gain FEL oscillators generating few cycle short, high intensity mid-IR pulses with tens of MHz repetition rates might become attractive tools in various strong field applications. In a recent study a mode-locked, coupled FEL oscillator scheme has been presented to generate multi-mJ level, ultra-short (<10 cycles) output pulses tunable within the entire IR region. The current work elaborates on an improved FEL oscillator scheme that can cope with the high power levels accumulated within the coupled cavity while operating unidirectionally, eliminating the feedback in the reverse direction. The various operational regimes of the coupled laser system are discussed.

INTRODUCTION

The objective of the study is to draw on the potential of the ERL based FEL devices to produce multi tens of mJ level, ultra-short (≤10 cycles) output pulses tunable within the entire IR region (and beyond) with at least several tens of MHz repetition rates. The latter would be a major step in overcoming the performance limitations of the current ultra-short laser technology in the high-field applications, a domain that is being dominated by conventional NIR/MIR sources. The achieving of the goal relies on taking advantage of the high powers deposited in the beam (average as well as per bunch) by a 100-200 MeV range superconducting ERL system operating at high repetition rates and elaborating on schemes with high extraction efficiency that would enable the generation of few cycle long intense radiation pulses.

In a recent study a high gain FEL oscillator scheme is investigated that encompasses two coupled oscillator cavities [1]. In general terms the system operates as an injection locked laser system whereby the first FEL cavity (master oscillator) provides a strong ultrashort, wide-bandwidth seed signal that is transmitted through the coupler mirror (less than a few percentage coupling ratio) into the amplifier cavity. The latter can be driven in different operational regimes. The most straightforward manner is using the second cavity as a passive pulse stacker cavity. In this mode its finesse is set to optimize the outcoupled pulse energy (unless an intracavity application is considered). On the other hand injecting the spent beam into the second FEL oscillator cavity where it further interacts with the optical pulse that is coupled in and building up within this cavity leads to the injection locked operation. In this operational modus the resultant radiation field circulating in the amplifier cavity can be approximated in the first order by summing up the coupled fields that are coherently accumulating and boosting up the intracavity power in an enhancement cavity (EC) and the field build up resulting from the injection locked FEL interaction. The extent of the latter contribution can be defined by adjusting the undulator and resonator parameters of the two cavities. In the studied cases the amplification effect based on the coherent pulse stacking of an EC turns out to be superior to the growth of the intracavity fields due to the FEL process. Note that unlike the latter, coherent pulse stacking does not suffer from a saturation mechanism that limits the amplification and the associated field build up over many roundtrips. (Reaching the *steady-state* in an EC is a different process than the FEL saturation.) It should also be emphasized here that prior to its injection into the amplifier cavity the beam already starts acquiring a relatively large energy spread since the master FEL oscillator is driven at zero cavity detuning and saturation is attained. Nevertheless, at the presence of the accumulating fields within the amplifier cavity and the broad band interaction with it, the spent beam's energy transfer into the radiation fields exceeds significantly the one due to the fresh injected beam's FEL interaction in the master oscillator, increasing accordingly the final beam energy spread.

In realizing the above mentioned operational regimes a nearly 100% percent coupling efficiency (in coupling the seed) is ensured while a decoupled, virtually reverse feedback free configuration is implemented. Our simulations that allow reverse feedback (bidirectional coupling) indicate a limit value for the coupling ratio back into the master oscillator at around 10^{-8} [2] in order to recover nearly the same performance that results from the fully decoupled case.

On the other hand the high intracavity power levels circulating particularly within the amplifier cavity necessitate designs that can cope with thermal related effects on the mirrors (distortion of the fields, damage at the mirror surfaces) by adopting proper measures in time and space. Whereas the average power can be controlled over the duty cycle (macropulses at lower duty cycle) it is also essential to increase the mode waist on the mirrors. In addition cryocooled laser optics developed for high power applications can be utilized to alleviate the thermally induced adverse effects.

COUPLED FEL OSCILLATORS

The composite resonator shown in Fig.1 is a special case of two coupled lasers in the weak coupling limit [1] (transmission of mirror B << 1.0). In order to incorporate the features that are briefly addressed in the introduction a hybrid cavity design is adopted. While the first cavity supports the Gaussian (fundamental) mode the second (amplifier) cavity is a Bessel-Gauss (BG) type cavity [3-5]. Here we take advantage of two salient features of the

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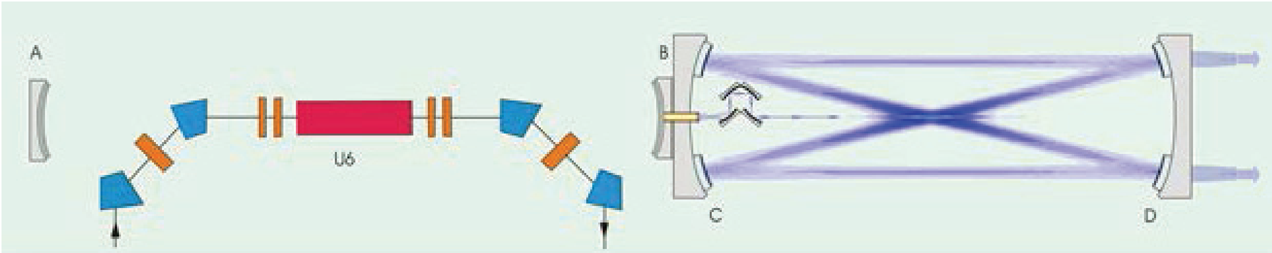

Figure 1: Schematic layout of the coupled cavities. Here the second cavity that supports the BG beam serves as a passive EC. The output is an annular beam.

BG cavities: i) the field distribution at mirrors C and D is an annulus with an approximately Gaussian radial intensity, ii) if an ordinary BG beam is imaged by a lens the outcome is a modified BG beam and vice versa [5]. All mirrors are dielectric mirrors with minimal absorption losses. The coupling mirror B has an optical waveguide/fiber optic placed at the beam axis that is terminated with an axicon on its tip. All transition surfaces (dielectric layer to fiber optic, axicon to free space) are individually impedance matched (coated) so to minimize any distortion of the reflected fields in the master oscillator (note that the coupling ratio is anyhow less than 0.01-0.02) and to maximize the coupling efficiency into the amplifier cavity (stressing here that this is not a hole coupling). The mirror lens set (optical delay line) incorporated into the amplifier cavity ensures the proper mode matching at the plane of coupling. Figure 2 shows the extent of the annular beam (normalized field Amplitude) at mirrors C and D for the wavelength range of interest and for a cavity length of ~26 m. One should also indicate at this point that the Gaussian cavity (master oscillator) too can be replaced by a BG type cavity. BG type cavities offer a wide range of beam manipulation means that however is not the topic of this report.

Mode-locking in FEL Oscillators Operating at Zero Cavity Detuning

A key aspect in our approach is that the master oscillator is driven in a single spike modus that is realized in a short pulse high gain FEL oscillator with perfectly synchronized optical cavity length (~zero cavity detuning) [6, 7]. In this regime that is dominated by high FEL gain, low cavity loss and optical pulse-electron beam slippage effects, the radiation stored in the cavity evolves into an ultrashort, intense spike. As demonstrated experimentally [7] this mode of operation enables also a high FEL extraction efficiency reaching up to many percentages which, along with a highly energetic electron beam, builds the first step towards achieving mJ level FEL pulses. The dynamics of an FEL operating in this regime is characterized by the so called short bunch limit [8]. As a result of the high gain FEL interaction, in the short bunch limit the spike width can become even shorter than the cooperation length $l_c = \lambda_r/4\pi\rho$; λ_r and ρ denote the radiation wavelength and the FEL parameter [8], respectively. Furthermore, as was demonstrated in Ref. 7, the FEL interaction induces a frequency chirp in the generated spike, making further compression of the pulse duration possible while bringing the pulse width ultimately down to a few cycles. Along with the mentioned high extraction efficiency, the generation of ultrashort (<10 cycles) spikes is an additional factor provided by the presented high gain FEL oscillator operated at perfect synchronism towards achieving high peak intensities.

Coherent pulse stacking as well as injection locked FEL amplification of the *frequency combs* in the seeded cavity are discussed in [1] and the references therein. It is worthwhile to turn the attention to the mode-locking process that leads to the formation of the described ultra-short, ultra-broad bandwidth, chirped optical pulses in the master oscillator. The fact that the high gain FEL operation at perfect synchronism enables the generation of ultrashort optical pulses that are propagating with a (nearly) self-similar shape from one roundtrip to the next indicates that the interaction can sustain and amplify a vast number of longitudinal cavity modes excited within an ultrabroad bandwidth (*frequency comb*) while a fixed phase relationship (phase locking) between all of them is established.

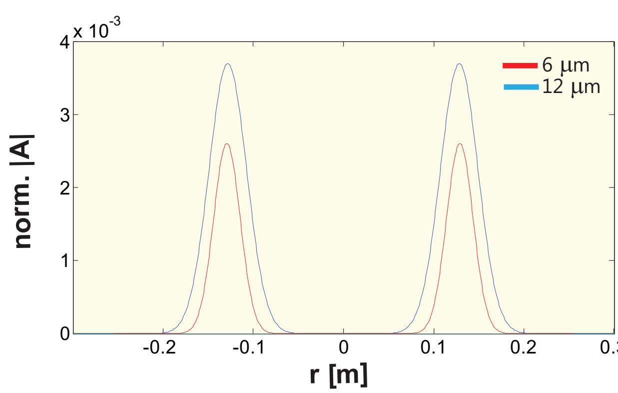

Figure 2: Plot of the norm. Amplitude cross section at the BG cavity mirrors. Keeping the tilt angle fixed annular beam's width and radius can be increased by lengthening the cavity.

The mode-locking process of frequency combs that is of interest here relies on a *self-starting* and *self-sustaining* phase and amplitude (loss) modulation. As already stated in [1], this *passive mode-locking* process is supported and sustained by the energy transfer from the radiation pulses to the particles that reach the bottom of the ponder-

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omotive potential well as they execute synchrotron oscillations with frequency $\Omega_s \sim P^{1/4}$ [9] in the phase space. The time scale of the process is dominated by the slippage of the optical pulse during half a synchrotron oscillation period (electrons absorbing energy from the pulse tail) and as such it is a pulse intensity dependant process [1, 2]. The time scale and magnitude of the loss changes dynamically in response to the pulse intensity and vice versa. The slippage dominated interaction leads also to a phase modulation manifested by the induced chirp in the optical pulse. The complex index of refraction guiding of the optically bunched beam [10] is also pulse intensity dependant in the exponential gain regime. Its evolution in the course of the high gain FEL interaction is an additional effect that needs to be accounted for in the overall analysis. As indicated in [1], it would be useful to model the combined non-linear, self induced phase and amplitude modulation process by the master equation approach for mode-locking [11] relating and contrasting the described high gain FEL dynamics at zero cavity detuning to mode-locking in ultrafast optics.

Whereas constraints are imposed on the generation of few cycle high intensity pulses by using atomic lasers for high field applications (arising from power scaling limits due to material damage of the gain medium and artificial modelocking elements, (undesired) intensity dependent nonlinearities, restricted operational wavelength range) the mode-locking process exploited in this study allows to overcome these limitations, opening up ways for pertinent new applications. On the other hand major challenges inherent to the FEL interaction in realizing the envisaged operational modus in the mid-IR spectral region are described in [1].

SIMULATIONS

Simulations are carried out using the FEL modeling that is based on the multifrequency expansion of the fields with no averaging carried out in the source term [1]. Since the modeling employs transverse mode expansion too, adopting the optical guiding approach [12] would allow more accurate predictions of the high gain FEL dynamics, even an oscillator is treated in our case. The transverse guiding effects are not taken into account in the results presented in this report.

The considered FEL scheme is assumed to be driven by a 100 MeV rf linac, ~80 pC-150 pC bunch charge , 100 fs (σ_z) long bunches with 0.5% energy spread (σ_E). For the sake of simplicity in transporting and injecting the spent beam for the injection locked operation transverse emittance is neglected. Planar undulator modules consisting of 10 to 23 periods (λ_u=6cm) with uniform fields are used in the respective resonators.

Figure 3 displays the temporal profile (at saturation) of the generated seed spike that is inherent to this low loss, ultrashort pulse, high gain FEL regime. Figure 4 displays the broadening of the spike's spectrum (at saturation) by increasing the bunch charge up to 150 pC. The spike duration shortens according to the scaling dependency $P^{-1/4}$ companied with a stronger chirp in the pulse. Note the down shift of the initial resonance frequency (~6μm) following the beam energy loss due the FEL interaction. In Fig.5, adjusting the loss and the slippage, the next satellite spike develops to a similar peak power level as the primary spike, exhibiting an evolution somewhat in analogy to the formation of limit cycle oscillations in the cavity detuned FEL oscillators at saturation.

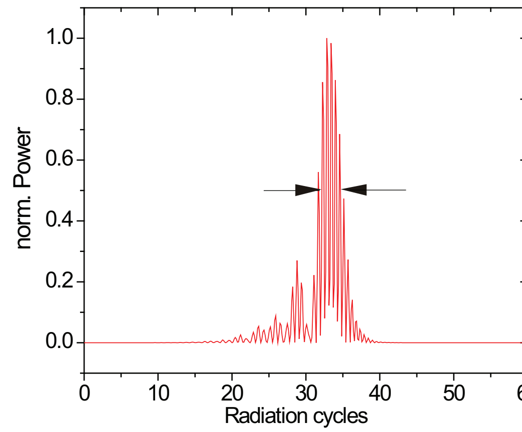

Figure 3: The seed spike's FWHM is around 3-4 radiation cycles.

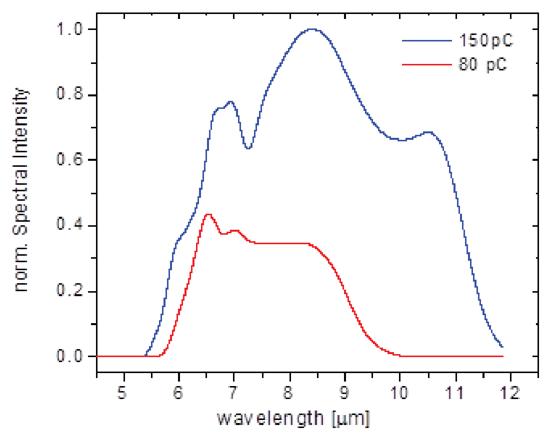

Figure 4: Pulse spectrum at saturation for 80 pC and 150 pC bunch charges.

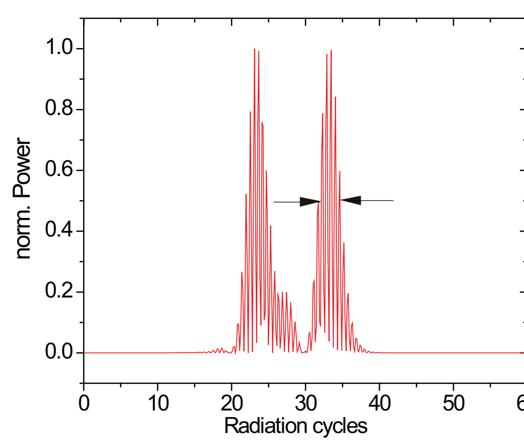

Figure 5: Double spike generation at saturation. The delay between the pulses amounts to ~200 fs.

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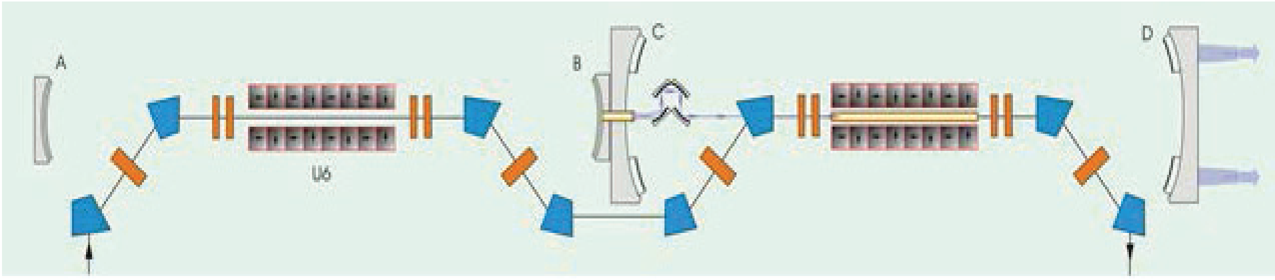

Figure 6: Schematic layout of the coupled injection-locked FEL cavities. By adjusting the settings of the resonator and the undulator modules in the respective cavities (basically cavity loss and slippage) the contribution arising from the injection locked FEL to the circulating power in the amplifier cavity can be varied. Note that the shown components are not scaled.

In order to amplify the BG beam (~ truncated Bessel beam) injected into the coupled cavity we employ a technology already developed for high power fiber lasers/optical waveguides. Bessel-like beams can well be generated by selectively exciting high order LP_{0n} fiber modes. The adopted approach here involves the use of hollow core photonic band gap (or photonic crystal) fibers/optical waveguides (HC-PBF/HC-PCF) [13] with a large core aperture (5.5-6.0mm). The large core aperture favors the excitation of higher order modes (HOM), exhibiting extremely low attenuation as well as low dispersion for the wavelength range of interest. It is also beneficial for very high power applications. On top of it, the technology of HC-PCFs offer enormous design flexibility in tailoring broadband dispersion characteristics (controlling dispersion and its slope, achieving ultra-low, ultra-flattened dispersion) and the implementation of highly efficient (>99%) grating based mode converters. The latter is crucial to enforce the gain medium (in addition to the injected Bessel beam) to couple selectively to the desired HOM along the interaction region. Matched doubled-chirped mirrors can be included into the resonator design for an additional dispersion control.

The injection locked FEL simulations carried out here assume the mode radial order ≥ 10. The schematic layout of the coupled oscillator FEL is shown in Fig.6. The delay line mirrors ensure the proper synchronization between the electron and radiation pulses and the proper mode matching of the seeded Bessel beam at the entrance of the HC-PBF (undulator entrance). The aperture of ~5.5-6 mm is chosen to allow a loss free transport along the undulator for a beam with 80 pC charge.

It is worthwhile to note at this point that the injected pulse's mode structure can be better matched by replacing the fiber optic/axicon configuration depicted in Fig.1 with a mode converter written HC-PBF of the desired radial order.

Figure 7 shows the pulse energy evolution of the outcoupled pulse at mirror D (The intracavity pulse energy amounts to nearly 1.5J). Here the contribution from the injection locked FEL interaction makes up less than 5% of the total pulse energy (which nevertheless exceeds by far the energy extracted from the electron

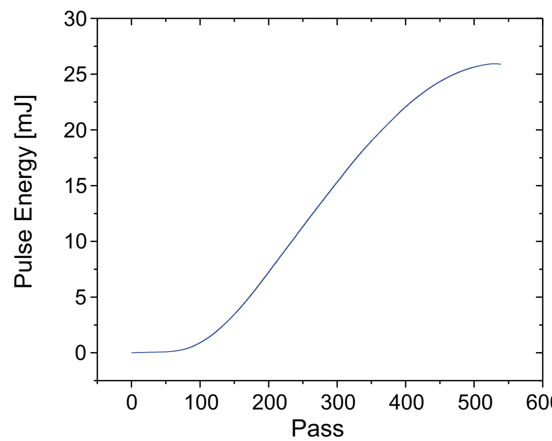

Figure 7: Outcoupled pulse energy evolution.

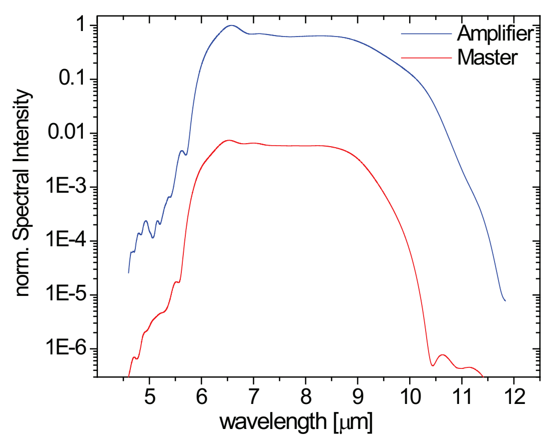

Figure 8: Frequency response of the injection locked amplifier cavity to the input seed wave whose temporal profile is shown in Fig. 3.

beam in the master oscillator). Figure 8 displays the frequency response of the injection locked amplifier cavity to the input seed wave. The truncation at 12 μm is due to the mirror reflectivity characteristics. By adjusting the undulator and resonator settings the contribution is increased up to ~20% for the BG beam as depicted in Fig. 9. Here, the pulse energy evolution of the BG beam, the Gaussian beam as well as the passive Enhancement

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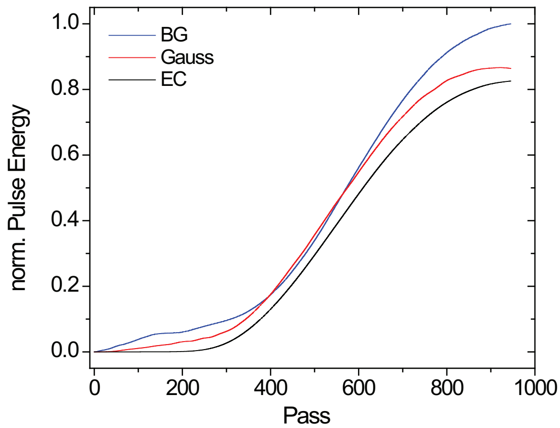

Figure 9: The pulse energy evolution in the amplifier cavity. BG refers to an FEL that is based on Bessel-like beam in the cavity. In the case of the Gaussian cavity it is assumed (hypothetically) that the reverse feedback vanishes.

Cavity are contrasted, respectively. The pulse energy is normalized to the maximum pulse energy attained by the BG beam.

A detailed description of the presented scheme along with the simulation results will be reported elsewhere.

CONCLUSION

In the presented study the used simulation model yields, under the described idealized conditions, Joule level intracavity as well as tens of mJ outcoupled high rep. rate ultrashort, broad bandwidth mid-IR pulses. The studied coupled FEL oscillator configuration enables efficient injection locked amplification of beams with large energy spread (dirty beams) at the presence of the accumulated, ultrashort, broad band, high intensity intracavity radiation pulses. Further studies focus on the following topics: i) rather than using the relatively low charge spent beam, injection of high intensity 'dirty' beams (using a different beam source/accelerator system) into the second cavity will push up the FEL saturation power, ii) increasing the intensity of the seed pulses (and the extraction efficiency) by replacing the Gaussian master oscillator with a Bessel-like beam cavity. In the latter case it might be sufficient to drive the second cavity only as a passive EC while reaching pulse intensity levels still useful for high field applications that are presented in Ref. [2].

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