PULSE CONTROL IN A FREE ELECTRON LASER AMPLIFIER

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Abstract

A significant progress has been made in controlling the properties of the radiation emitted by a FEL amplifier. Experiments have demonstrated the possibility both to increase the temporal coherence and to reduce the amplifier length to reach saturation, by seeding it with an external source. This may be a solid state, short pulse, laser (Ti:Sa,OPA..), doubled or tripled in a crystal, or a high order harmonic pulse generated in gas. The coherence improvement and the increased compactness of the source are only the first beneficial offspring of this marriage between the optical laser world and that of FELs. Non-linear effects in the seeded FEL dynamics may be exploited to shorten the pulse length beyond that allowed by the FEL natural gain bandwidth. Multiple seed pulses can be used to generate pulses whose temporal distance and properties are also controlled. Similarly, the FEL gain can be adapted to match the seed properties by tailoring the electrons phase space to generate ultra-short output pulses at unparalleled intensities.

INTRODUCTION

The free electron laser is a very special laser amplifier reling on a quasi “medium-free” amplification mechanism. The active medium is indeed constituted by electrons interacting with the ponderomotive potential made by the undulator and the laser field itself. This fact allows great control on the resonances coming into play and the amplification process may be designed in an extremely wide spectral range. Single pass FELs operate in mirrorless configurations where the radiative interaction of electrons is mainly that with the laser optical electromagnetic wave at the resonant frequency, permitting the lasing process down to the VUV or X-ray spectral range. FEL light sources dedicated to user experiments are fully functional both in the hard X-rays, such as LCLS and SACLA [1, 2], and in the soft X-rays, as FLASH and FERMI [3–5]. After a first phase where the main scientific and technical challenge was that of achieving sufficient gain to reach saturation, the problem shifted to that of gaining full control of the properties of the emitted radiation. We are now learning how to influence the amplification process and modify the properties of radiation according to the needs of experiments where the FEL light is the investigation tool. Several experiments have demonstrated the possibility of both increasing the temporal coherence and reducing the amplifier length required to reach saturation, by seeding the amplifier with an external source. The electron beam, can be shaped to influence the gain spectrum and effectively modify the gain frequency bandwidth to generate ultrashort pulses, even beyond the limit posed by the intrinsic gain bandwidth of the FEL process. Other experiments have shown the ability of the FEL to act as harmonic converter, extending to very high order the emission of harmonics. In this contribution we have reviewed some of the experiments carried out at SPARC and FERMI, that were done within this specific scientific framework.

SEEDING AND HARMONIC GENERATION

The FEL conversion from electron kinetic energy to energy of the optical wave has the typical behavior of an instability, with an exponental growth regime followed by a saturation process [6–9]. The gain of the instability, as resulting from the one-dimensional theory and in the cold beam limit, is described by the universal scaling parameter ρ_{fel} [9], related to the power e-folding (gain) length L_G by the relation $L_G = \lambda_u/(4\pi\sqrt{3}\rho_{fel})$. When the process starts from the electronic noise, after an exponential growth over a distance $L_{sat} \sim 20\, L_G$ the signal saturates at a power $P_{sat} \sim \rho_{fel} P_{beam}$ where $P_{beam} = I_{peak}\gamma\, m_0 c^2/e_0$ is the power carried by the electron beam. The natural line width of the output radiation from the SASE process in the classical regime is of the order of the parameter ρ_{fel}. The frequency spectrum of the emitted radiation corresponds to the white noise associated to the initial electron random distribution, filtered by the FEL gain bandwidth. Self amplified spontaneous emission output usually has poor longitudinal coherence, with a temporal and spectral structure consisting of a series of spikes uncorrelated in phase or amplitude [10–12].

This natural evolution of the FEL process may be influenced at startup by seeding the amplifier with an external source. The coherence properties of the seed are transferred to the electron modulation, leading to coherent emission at the undulator resonance and at its harmonics. The input seed, in order to be effective, must be intense enough to dominate the beam shot noise associated intensity, which may be derived according to the model in [13] and is given by $I_{sn} \approx 3\,\omega\,\gamma\, m_0 c^2 \rho_{fel}^2$, where ω is the FEL resonant frequency.

Harmonic generation in gas [14] is one of the most promising methods to generate radiation in the VUV region of the spectrum, and this method was used at different facilities to seed directly an FEL amplifier at wavelengths ranging from 160 nm down to 38 nm [15–19]. Seeding at the shortest wavelengths has pointed out the increasing difficulty in overcoming the electron beam associated shot noise power, which is linearly proportional to the photon energy. An alternative is to seed the FEL at longer wavelengths and exploit the harmonic generation mechanism to reach the desired spectral range. The first idea on implementing an FEL as an harmonic converter appeared in [20]. Afterwards different schemes involving higher order harmonic bunching and harmonic generation were proposed and studied both theoretically and experimentally by several authors [21–27]. Harmonic generation combined with a high gain FEL am-

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plifier (HGHG [26]) was investigated in two experiments done at Brookhaven [28, 29] that are considered important milestones in the development path of seeded FELs amplifiers. This development led to the design and construction of FERMI, the first seeded FEL user facility, that produced the first light in 2010. The HGHG cascade scheme is implemented in FERMI FEL-1, to generate fully coherent radiation pulses in the VUV spectral range [4]. The seed signal, continuously tuneable typically in the range 230-260 nm, is obtained from a sequence of nonlinear harmonic generation and mixing conversion processes from an optical parametric amplifier. The radiation resulting from conversion in the FEL up to the 13th harmonic is routinely delivered to user experiments [30]. The HGHG cascade may also be seeded by two temporally separated pulses. The FEL produces multiple, virtually jitter free, VUV pulses which may be separated in frequency within the FEL amplifier bandwidth. The generation of two-colour extreme ultraviolet pulses of controlled wavelengths, intensity and timing was demonstrated in a pioneering experiment where the time evolution of a titanium-grating diffraction pattern was studied by tuning the two coherent pulses to the titanium M-resonance [31].

With a double conversion stage based on the fresh bunch injection technique concept [32, 33] FERMI FEL-2 [5] extends the spectral range of the seeded FEL facility down to 4 nm at the first harmonic of the final radiator, providing radiation to experimental stations in the soft-X ray region of the spectrum.

SHAPING THE FEL GAIN

Single Spike

Tailoring the longitudinal properties of the electron beam distribution is another method of controlling the output characteristics of the FEL pulse. An example is provided by the "single-spike" operation where lasing is enabled in a region of the bunch comparable or shorter than the FEL cooperation length [34, 35]. Some pulse shortening methods rely upon purposeful degradation of the FEL gain outside a small temporal region; after several gain lengths, this region will dominate the FEL output [36]. However, the single-spike approach may be characterized by a very short gain length, due to the high brightness beams achievable when the bunch charge is reduced (< 10 pC) to shorten the pulse length. This generally implies an efficient radiation production, but also a relatively small absolute pulse energy. On the other hand, an alternative option consists in introducing a linear correlation (chirp) in the electron longitudinal phase space and in tapering the undulator to enable the preservation of FEL gain along a determined spatio-temporal path [37, 38]. This scheme combines therefore electron beam energy chirp with a judiciously-chosen undulator-field taper, i.e., a smooth variation of peak magnetic field along the beam propagation axis. The scheme was demonstrated at SPARC [39], where it was shown the possibility of generating isolated radiation spikes in a single pass FEL operating in SASE mode, without an increase in the gain length or a loss of efficiency, but in fact with an increase by a factor of 20 in the pulse energy. This was due to the involvement in the gain process of a longitudinal extension of the e-beam comparable to the slippage length. This efficiency improvement was accompanied by a narrowing of the spectral width in a single moded spectral shape. The properties of the radiation in these conditions were further investigated in [40] where a FROG diagnostic was implemented to simultaneously measure the temporal and spectral content of the radiation along with the pulse's phase information. A time bandwidth product of about 1.2 was measured, with a pulse duration of about 100fs (fwhm), compatible with the spectral width independently measured.

Chirped Pulse Amplification

An alternative way to obtain ultrashort pulses, while preserving the FEL interaction over a longitudinally extended region of the electron bunch, is by optically compressing the radiation after amplification. An electron beam with a nonzero energy chirp, seeded by a properly chirped optical pulse, may generate a radiation pulse which may be then compressed in an additional optical stage (the compressor). This method corresponds to the chirped pulse amplification technique implemented in solid state lasers. Here the issue is not that of reducing the peak power in an active medium, but to allow the use of an extended electron beam longitudinal region, increasing the active bunch charge, without compressing the electrons to the ultimate limit. Chirped pulse amplification (CPA) in FEL amplifiers was proposed originally in [41] and further studied in the framework of a SASE amplifier in [42]. Critical is the efficiency of the the optical compressor which has also to be tunable in the wavelength region of interest.

Generation of Trains of Ultrashort Pulses

Different techniques relying on concepts adapted to FELs from mode-locked cavity lasers, have been proposed for modifying the characteristic time scales of x-ray pulses beyond the FEL bandwidth limitation [43–45]. These methods foresee the generation of trains of high peak coherent power flashes with large contrast ratio by applying a series of spatiotemporal shifts between the co-propagating radiation and the electron bunch. This undulator configuration corresponds to a multiple resonances-undulator [46, 47], and from the point of view of the spectral gain distribution, it has some analogies to the gain distribution of a double-peaked electron energy distribution. An experiment was carried out at the SPARC FEL [48], where the double-peaked electron energy spectrum was obtained by the laser comb technique, in the velocity bunching regime [49, 50]. The electron beam, constituted by two short and balanced bunches, is extracted from the linac accelerating section near the maximum compression. At this point, the two beamlets, temporally superimposed in the longitudinal phase space, are characterized by a different value of the mean energy. The SASE emission corresponds to that of the two simultaneously lasing ultra-short electron bunches in single spike regime, separated in resonant frequency by a relative distance larger than the ρ_{fel} parameter. The output radiation corresponding to the optical interference of the two pulses, was measured by a FROG diagnostics, and presented the expected comb temporal distribution with a corresponding spectral structure broader than the single beam amplifier bandwidth [51]. This method, which has been tested at SPARC FEL in the infrared, could be extrapolated in the production of sub-femtosecond pulses in the X-rays.

SATURATION AND SUPER-RADIANCE

At radiation saturation, the exponential gain process is replaced by a cyclic energy exchange between the electron beam and FEL radiation, with the period corresponding to that of the longitudinal synchrotron oscillation of those electrons trapped in the ponderomotive well. We may distinguish between a situation where the radiation pulse length is much longer than the slippage distance covered during one period of synchrotron oscillation, and the situation where the pulse length is comparable or shorter than this distance. In both cases the pulse shape is strongly affected by saturation effects.

Small Slippage: Pulse Splitting

In the first case we may neglect the fact that radiation slips over the electron current. Saturation effects, intended as over-bunching in the longitudinal phase space, may be induced in a HGHG FEL already at the entrance of the final radiator, by increasing the seed power or by increasing the dispersion in the chicane after the modulator. In these conditions the temporal distribution of the modulated electrons goes through a wave-breaking process at the central peak, while the temporal edges where the seed power is lower, may contain the correct density modulation at entrance to the radiator to produce two satellite pulses which are amplified in the radiator. This regime of operation was originally investigated in [52] and studied in combination of a frequency chirped seed pulse in [53]. In this configuration, the FEL is seeded by a powerful laser pulse carrying a significant frequency chirp. As a result, the output FEL radiation is split in two pulses, separated in time (as in the previous case) and having different central wavelengths. The spectral and temporal distances between FEL pulses can be independently controlled, providing the possibility of using the FEL at the same time as a pump and as a probe with multicolor synchronized pulses, where the two output pulses can be independently diagnosed with dispersive optics [54].

Large Slippage: Super-radiance and Harmonic Heneration

In the mid 1990s a number of papers analyzed theoretically and numerically the consequences of the slippage on the pulse evolution in a FEL amplifier [55–57]. It was pointed out the existence of a super-radiant regime where a short optical pulse slips over the electron beam and increases its energy while keeping a self-similar shape. In this regime, the radiation pulse has a peak power increasing with the square of the distance along the undulator and a longitudinal width decreasing with the inverse square root of this distance. The radiated power is proportional to the square of the electron current. The pulse spectral bandwidth increases and the pulse undergoes longitudinal focusing. This regime was studied at BNL in an experiment where the NISUS undulator was seeded by an infrared Ti:Sa laser of 150 fs of pulse duration [58]. Pulse shortening down to about 82 fs was observed, and the pulse energy scaling vs distance along the undulator was verified. Another important feature of this regime is in the generation of harmonics of high orders and the behavior in a cascaded FEL configuration [59]. In a cascaded FEL operating in the super-radiant regime the distinction between the modulator and the radiator typical of common HGHG-FEL schemes is no longer appropriate: the steps of energy modulation, density modulation and emission take place simultaneously at different locations along the optical pulse. As in steady state FEL dynamics, the density modulation induces intense emission of radiation at higher order harmonics, but this occurs during the pulse propagation along all the undulator. When the electron beam passes from one stage of a cascade to the next, the region of high density modulation will emit a short pulse of coherent radiation at the new resonant wavelength. This pulse slips on a fresh portion of the electron beam and may be amplified in the exponential gain regime or, as happens in most cases, may be intense enough to saturate and enter the super-radiant regime.

The behavior of the single-pass FEL in deep saturation has been studied at SPARC by seeding the entire amplifier with six undulators tuned at 400 nm with short laser pulses with peak power of the same order of the FEL saturation power. The observation of harmonic emission up to the 11th order was reported in [60]. Later on the behavior of the system in a HGHG configuration was also studied at SPARC [61]. In a FEL cascade, at the transition from a modulator to a radiator, the high frequency components in the leading edge of the pulse are expected to induce the growth of a new super-radiant pulse at the harmonic frequency, which then grows, according to the scaling relations, in the next undulator. The six SPARC undulators were configured to establish an HGHG FEL, with the first undulator tuned with the resonance at 400 nm, playing the role of modulator, and the other five tuned at 200 nm, as radiators. The evolution of the pulse in the radiator was studied by measuring its energy and spectral properties. Energy per pulse substantially larger than the FEL saturation energy, without applying any undulator taper, was observed. An energy scaling vs the longitudinal position along the undulator of the type $E \propto z^{3/2}$ was measured, in satisfactory agreement with the theoretical model and simulations. Successful generation of high harmonic radiation output in a harmonic cascade configuration [62] has been recently accomplished at FERMI, both in FEL-1 [63] and FEL-2 [64] and harmonics up to order 65 and 192 of the input seed were respectively observed.

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