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FREE ELECTRON LASERS: DEVELOPMENT AND APPLICATIONS

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Abstract In this paper I will try to give an overview of the FEL status and applications; I will then discuss some of the the work being done for its further development, in particular in the soft X-ray region.

1. INTRODUCTION

The Free Electron Laser (FEL) uses a beam of relativistic electrons passing through a transverse periodic magnetic field, an undulator, to exchange energy with an electromagnetic radiation field(1,2). In the most common case the energy is transferred from the electron beam to the radiation, to amplify it. It is also possible to transfer energy from the radiation to the electrons, thus accelerating the beam (Inverse FEL)(3,4). The energy exchange requires that a relationship between the radiation wavelength, λ, the beam energy $E = mc^2\gamma$, and the undulator period, λ_u, be satisfied. This relationship, the synchronism condition, is approximately $\lambda \sim \lambda_u/\gamma^2$, and shows that the FEL wavelength can be easily changed over a large region, from centimeter to nanometer, by simply changing the beam energy. Since the radiation pulse structure reflects that of the electron beam, it is also easy to produce pulse lengths ranging from almost CW, using an electrostatic accelerator, to picosecond, using an RF linac. In addition, for a high energy electron beam, it is easy to obtain large peak power, on the order of GW to TW; this means that also when the efficiency of energy transfer is small, the FEL can easily produce high peak power electromagnetic radiation. Contrary to what happens in an atomic or molecular laser the energy that is not transferred to the radiation can be disposed of out of the undulator, or recovered. The FEL has thus become a conceptual and practical alternative to other radiation sources, like microwave tubes and lasers, and can extend the operational range of both of these systems. This point is illustrated in Fig. 1, which compares the FELs and other radiation sources, microwaves tubes, lasers, undulator radiation from high brightness synchrotron radiation storage rings, and from plasma based X-ray lasers at Livermore and Princeton. The FEL performance level is partly based on experimental data, and partly extrapolated from our present knowledge of the physics and technology of this system. This second case applies in particular to the far UV and soft X-ray region.

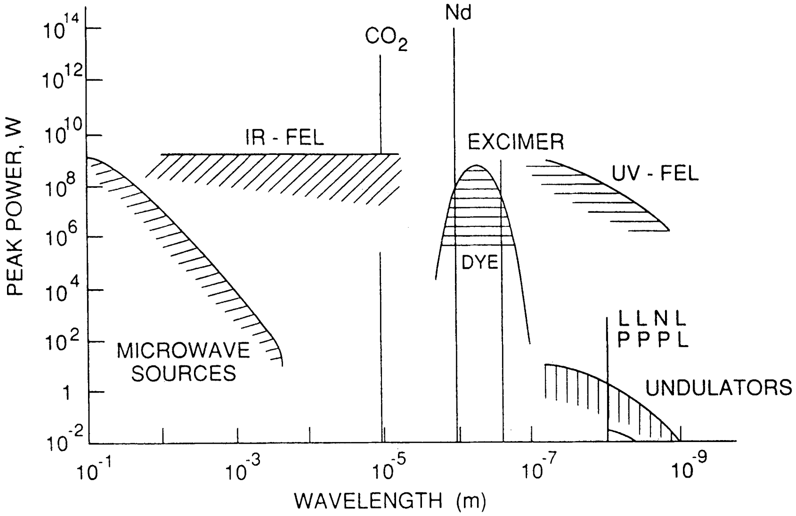

Figure 1.

2. FEL APPLICATIONS

One can see from Fig. 1 that there are two main regions of interest for FELs applications, where they can be far superior to other sources: one is in the IR and millimeter to centimeter region; the second is in the short wavelength region, below 100 nm. A summary of some of the applications is given in Tables 1 and 2. The millimeter to centimeter region is the most interesting for applications to high gradient linacs in the 30 GHz or higher frequency region, using the Two Beam Accelerator scheme(5,6,7,8). At shorter wavelengths, around 10 micrometer, the FEL could be used to drive an Inverse Free Electron Laser accelerator(3,4).

The far and near infrared region is also important to chemistry, solid state physics, materials science, and medicine, as has been recently discussed at a Workshop held at the Lawrence Berkeley Laboratory(9). The main conclusion of this meeting was that a FEL in the wavelength region of a few μm to about 40 μm, with a picosecond pulse length, peak power of several tens of MW, a small (transform limited) linewidth, and good stability and reproducibility would be a unique research instrument. While the wavelength range and peak power are already demonstrated, work needs still to be done to show that the reproducibility and line width are in hand.

The VUV region is again important for chemistry. For pulse length of one picosecond or less, and large peak intensity, one can, for instance, perform fast spectroscopy and fast timing experiments in the region of 50 to 100 nm. The region around 1 to 5 nanometers would be particularly useful for X-ray microscopy and holography. X-ray microscopy of biological samples will produce images resolving cellular substructure in the natural state, without dehydration or staining, and on a picosecond time scale, before the hydrodynamic expansion of the sample becomes important. If one can produce even shorter wavelengths, below 1 nm, with the required intensity and spectral characteristics, one might be able to sequence DNA pairs by direct imaging.

TABLE 1.

FEL Applications		
Condensed Matter	Surface Science	
	-Catalysis	IR
	-Adsorption	IR
	-Selective excitation of surface layer or adsorbed molecule	IR
	Semiconductors	
	-High Tc SC bandgap	IR
	-Carrier dynamics	IR
	-electron gas dynamics at metal-insulator junction	IR
	Superconductors	IR
	Magnetic Properties	IR
Chemistry	Molecular Vibrational Excitation	IR
	Reaction Dynamics	IR
	Photochemistry	IR
	Molecular Cluster, Van der Waals - molecule	IR
	Electronic excitations	UV
	Raman Spectroscopy	UV
	Crossed Photon-Molecular Beams	UV
Biology	Microscopy, Holography, Cellular Dynamics	1 – 3 nm
	DNA sequencing	0.1 – 1 nm
Medecine	Surgery	3 μm
	Photoherapy-Selective absorption in pigmented elements	0.7 – 1 μm

3. FEL STATUS

The first operation of a FEL was obtained in 1976, by Madey and coworkers(10,11) at infrared wavelength. During the 13 years that have passed since many more FELS have been successfully built and operated at wavelength ranging from the centimeter to the UV, and power levels ranging from the GW to mW. A complete review of these experiments can be found in reference 1, and also in a recent paper by Roberson and Sprangle(12). Here we will limit ourselves to mention some of the main results.

TABLE 2.

High Power FEL Applications		
Accelerators	Inverse FEL	1 – 100 μm
	TBA	1 – 10 mm
Fusion	Heating	0.1 – 1 mm
	Current drive in Tokamaks	0.1 – 1 mm
	ICF	0.1 – 0.5 μm
Non-linear QED studies		1 – 10 μm

FELs use different types of electron accelerators, varying in energy from about one to hundreds of MeV. Pulse-line diode are being used in several laboratories, including NRL(13), Columbia(14), MIT(15), Ecole Polytechnique(16), to produce radiation in the microwave region, with peak power of tens of MW and efficiencies up to 20%. The experiments at Columbia have also studied the effect of sidebands and of optical guiding(17).

Induction linac have been used at NRL(18,19) and LLNL. The technology of this accelerator has been greatly developed at Livermore, where experiments are being done on both the ETA (4.5 MeV, 1 KA, 30 ns pulse), and ATA (50 MeV, 10 KA, 70 ns). Experiments on ETA using a 10 cm period, 3 m long undulator have produced almost 100 MW, at 9.6 mm, using a constant field undulator configuration; changing to a tapered field configuration raised the power to about 1 GW, with an efficiency of 34%(20,21). The ATA is being used to operate at a wavelength of 10 μm(22); this group has reported peak powers in the 10 MW range, and the observation of optical guiding. Induction linac experiments are also being carried out in Japan(23).

A FEL driven by a van de Graaf electrostatic accelerator has been built at the University of California at Santa Barbara by Elias and coworkers(24,25), and is now being used as a dedicated facility for research. It provides tunable far infrared radiation between 0.1 and 0.5 mm, with peak power of about 10 KW. The beam energy varies between 2 to 6 MeV, with a current of 2.6 A, and a pulse length of a few to many μs. This long pulse length is achieved by recovering the beam after it goes through the undulator, decelerating it, and collecting it back in the high voltage terminal. In this way the charging current needs only to compensate for the electrons lost in the undulator, beam transport, and deceleration column. This long pulse length has permitted this FEL to obtain a very narrow line width, reported to be as small as 10^{-8}.

The Stanford superconducting RF linac was the accelerator used for the first FEL in 1976-77, and is still being used now by a Stanford-TRW group. This group has reported the operation of the first visible FEL, with a power of 21 KW at 520 nm(26). Room temperature linacs have been used in the following years at Stanford(27,28,29), Los Alamos(30,31), Boeing(32) to drive FELs from 35 μm to the visible, with peak powers up to 40 MW, and pulse length as short as one picosecond. Both oscillators and master oscillator power amplifier configurations have been used. Optical guiding, sidebands and harmonic generation have been observed. The RF linac can provide high quality beams of energies from a few MeV to GeV, to drive FEL in the infrared, visible or UV spectral regions. They could also be used in the future as drivers for Soft X-ray FELs, as will be discussed in Section 4. The short pulse duration, from picoseconds to tens of picoseconds, is a desirable property for many research applications.

The first operation of a FEL in a storage ring was obtained on ACO(33,34); the lasing wavelength covered the visible and near UV, with average power of about 50 mW, a gain of about 1% or smaller; the ring energy varied between 160 and 224 MeV, with currents in the range of tens of milliampere. To obtain the largest possible gain the undulator was built as an optical klystron(35,36), with a dispersive region between two undulators, to speed the beam bunching. The same undulator configuration has also been used to generate harmonics of a given input laser, which modulates the beam energy(37). More recently(38) another FEL has operated on the Vepp3 ring at Novosibirsk, reaching the lowest lasing wavelength for an FEL, 240 nm. This FEL covers the wavelength region 690-240 nm, and uses again an Optical Klystron configuration to reach a small signal gain per pass as large as 10% at 600 nm, and 2.5% at 240 nm.

This short review shows that the FEL is rapidly becoming a useful and used radiation source, and that its basic physics and technology is well understood. Much work is also being done to continue to improve it, extend its mode of operation and better understand its physics. I want to mention here some of this work, while the extension to short wavelength will be discussed in the next section. A gas loaded FEL has been built at Stanford by Pantell's group(39), and has lased in the region of about 3 to 4 μm. It uses a gas to modify the synchronism condition, and it can be tuned by changing the gas pressure. It requires a smaller beam energy for given wavelength than a standard FEL. Much progress has also been achieved in the construction of undulators, and they are now being extended to shorter periods, in the millimeter or submillimeter region(40), using either permanent magnets or electromagnets. Electromagnetic undulators have also been proposed, using microwaves(41) or high power lasers(42,43,44). In the theory area one can mention the studies of superradiance(45,46), an effect that can be obtained in short bunches because of the difference in velocity between electron and photons.

4. SOFT X-RAY FEL

As one can see from Fig. 1 and the discussion of the FEL application in section 2, a X-ray FEL is a most attractive development, and extensive work has been dedicated to it by several groups(47,48). The basic problem of a X-ray FEL is the decrease of gain with wavelength. In addition the optical cavity used in a FEL oscillator becomes very lossy, because of the lack of good mirrors at wavelength below 100 nm. To compensate for this effects one is forced to have high gain, i.e. to use electron beams with large peak current, and at the same time small emittance and energy spread. The road to a X-ray FEL requires the development of electron beams with unprecedented characteristics.

In this section discuss the FEL scaling laws, using a simple one dimensional model to describe the FEL physics in the high gain regime(49,50), which is the only one of interest for this application; effects like diffraction, undulator imperfections and other also have to be included in a real design. The notations we use are those of reference(50) and are: Beam particle density, n_e; undulator field, B_u; undulator parameter, $K = eB_u\lambda_u/2\pi\ mc^2$; undulator frequency, $\omega_0 = 2\pi c/\lambda_u$; beam plasma frequency $\Omega_p = (4\pi r_e c^2 n_e/\gamma)^{1/2}$.

With these notations, and considering for simplicity a helical undulator, we can write the FEL synchronism condition as

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1+K^2) \tag{1}$$

In the 1-D theory , and for a cold beam, the radiation field in the undulator grows exponentially until it saturates; the exponential gain length, LG, and the saturation are determined by one quantity(50),

$$\rho = \left(\frac{K}{4\gamma}\frac{\Omega_p}{\omega_0}\right)^{2/3} \tag{2}$$

the FEL parameter. The gain length is

$$L_G = \frac{\lambda_u}{4\pi\rho} \tag{3}$$

The laser power at saturation, P_L, is related to the beam power, P_B, by:

$$P_L \approx \rho P_B \tag{4}$$

and the saturation length is

$$L_s \approx \frac{\lambda_u}{\rho} \tag{5}$$

When we introduce energy spread and 3-dimensional, diffraction effects, we can still approximately use (3),(4), and (5) if some additional conditions are satisfied(51):

a) limit on beam energy spread: $\delta_E/E < \rho$,

b) limit on beam emittance: $\epsilon < \lambda/2\pi$,

c) condition for optical guiding: $Z_R/L_G \gtrsim 1$,

d) $\lambda_\beta > L_G$,

where $Z_R = \pi\alpha^2/\lambda$ is the Rayleigh range, and a is the beam radius, and λ_β is the wavelength of betatron oscillations in the undulator. The gain length is a very important quantity; it determines the scale length over which effects have to occur to influence the exponential growth rate; all effects which take place over a distance larger than the gain length will have very little effect on the FEL performance.

In the design of a FEL we have to maximize ρ for a given wavelength and beam characteristics. To this end we rewrite it using the beam invariants ϵ_N, ϵ_L, transverse and longitudinal normalized rms emittances (we assume for simplicity a cylindrically symmetric beam), and the longitudinal brilliance(51,52)

$$B_L = \frac{eNc}{(2\pi)^{1/2}\epsilon_L} \tag{6}$$

Using these quantities we obtain

$$\rho = \left\{ \frac{\lambda}{4\pi} \frac{K}{1+K^2} \left(\frac{\sigma_E}{E} \right)^{1/2} \left(\frac{4\pi B_L}{\lambda_\beta \epsilon_N I_A} \right)^{1/2} \right\}^{2/3} \gamma \tag{7}$$

where $I_A = ec/r_e$. It is interesting to notice that the dependence of ρ on λ is not strong, so that a FEL at short wavelength seems feasible; in addition (7) shows that it is convenient to use a large beam energy. The cost of using a large beam energy is that, for the same wavelength, we have to increase the undulator period, and the undulator becomes longer. However, since $N_u \sim 1/\rho$ the undulator length increases only linearly with the beam energy.

TABLE 3.

Soft X-ray FEL	
Wavelength, nm	25
Electron energy, GeV	1.02
Normalized Emittance, mm mrad	1
Longitudinal Brilliance, A	200
Energy spread, %	0.001
λ_β, m	1
ρ	0.0012
Undulator Period, cm	1
Gain Length, m	0.75
Undulator Length, m	8.1
Rayleigh Length, m	0.62
Beam Power, GW	400
Laser Power, MW	480

It is also convenient to make λ_β small, but this can lead to a reduction of gain, except when the focusing is provided only by the undulator field(53); in this case, however, we have usually

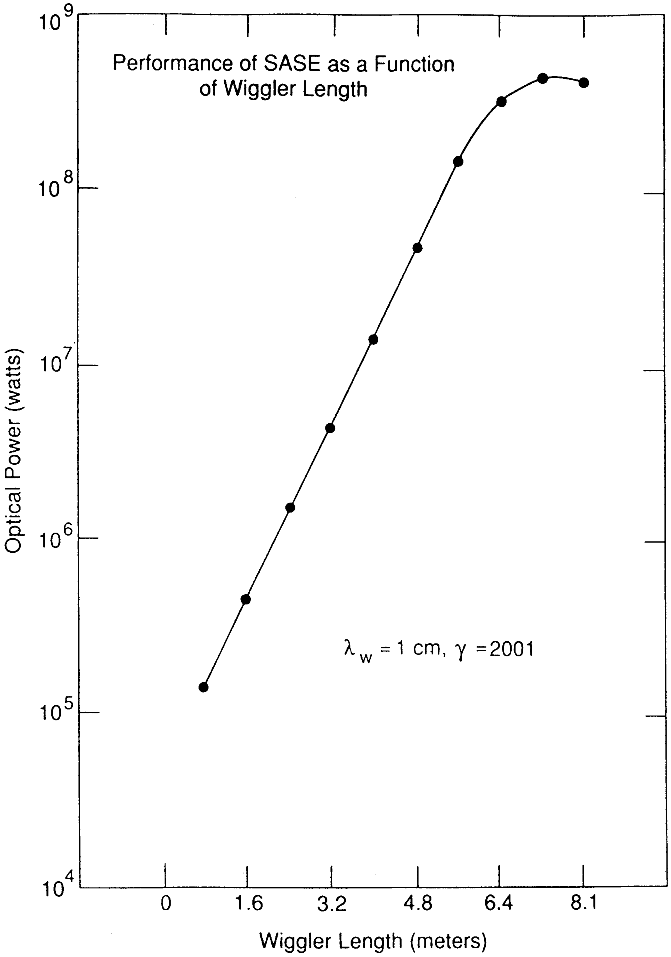

Figure 2.

$\lambda_\beta >> L_G$. To increase ρ it has been proposed to use extra focusing, which can be obtained with external focusing elements, like quadrupoles(51), or, as proposed by Barletta and Sessler(54), with ion focusing. To design the FEL there is also another choice to be made for the FEL mode of operation. One possibility is to use an oscillator configuration, with an optical cavity(55), the other is to operate in the Self Amplified Spontaneous Emission (SASE) mode(56). The oscillator requires a smaller gain and a shorter undulator than SASE, if the optical cavity has small losses, and this condition is difficult to satisfy at short wavelength because also the best multilayered mirrors have reflectivity of about 50%, and they are easily damaged. This damage can be enhanced by the the small laser spot size, and the correspondingly high power density of the radiation. To increase the mirror reflectivity Newnam has suggested to use multifaceted metal mirrors operating by total external reflection(57). Another improvement can be made changing the optical cavity configuration from a two mirror design with near perpendicular angle of incidence, to a ring resonator with many mirrors and glazing angle of incidence(55). SASE avoids the mirrors and optical cavity problems, at the cost of using a longer undulator. Several SASE based designs have been made(51,58); an example of such a system is given in Table 3.

Numerical simulations have also been done to determine the effect of errors in the undulator, and of beam emittance and energy spread, on the FEL performance. One set of calculations(58) was done using the FEL parameters of Table 3. In Fig. 2 we show the laser power versus undulator length, peaking at about 500 MW. Doubling the emittance would reduce the output power by about a factor of two, and doubling the energy spread would reduce it by about a factor of 10. The effect of wiggler field errors is estimated assuming that one can correct the trajectory but not the phase errors; in this case field errors on the order of 0.2% can be tolerated without any appreciable reduction in output power. A soft X-ray FEL will thus require the fabrication of long, high accuracy, high field undulators, with precision beam control. The considerable progress achieved in this area in the last few years let us believe that this can be done. As an example an 80 period, two meters long undulator built by Rocketdyne for MarkIII FEL(59), has demonstrated uncorrelated field errors which would satisfy our requirements. The possibility of using an Optical Klystron configuration for a high gain SASE FEL has been recently suggested; Fig. 3 shows how this system can reduce the undulator length by about a half.

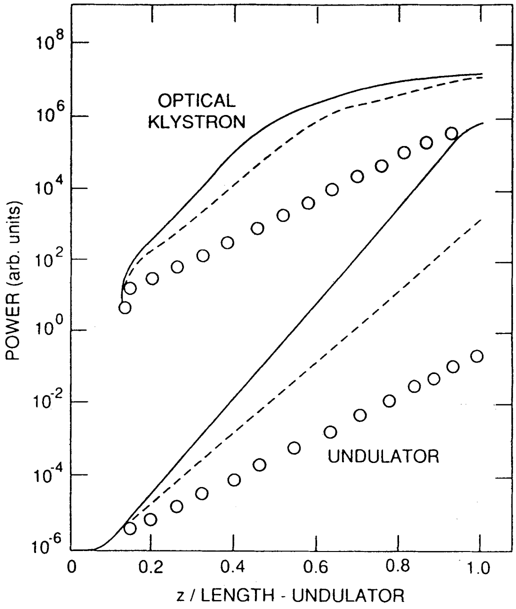

Figure 3.

The most stringent requirements for the realization of a X-ray FEL are those on the electron beam. A high beam quality, as shown for instance in Table 3, is needed to obtain a value of ρ in the range of 0.001. Two routes to high density electron beams are being followed, using storage rings(47,61,62) at Duke University, Dortmund and Berkeley, or linacs at Los Alamos, Brookhaven and UCLA(55,58). These have been reviewed at a Workshop held at Brookhaven in 1987(63).

As an example of small emittance, high current storage ring we can consider the SLAC damping ring(64),with an energy of 1.2 GeV, normalized emittance of 20 mm mrad, and a longitudinal brilliance of 120 A. In a ring emittance and longitudinal brilliance are coupled, and when reducing one we also reduce the other(65). Some new ideas to overcome this limitations, like wiggler rings(66), were also discussed at the Brookhaven workshop, and work is continuing in these directions.

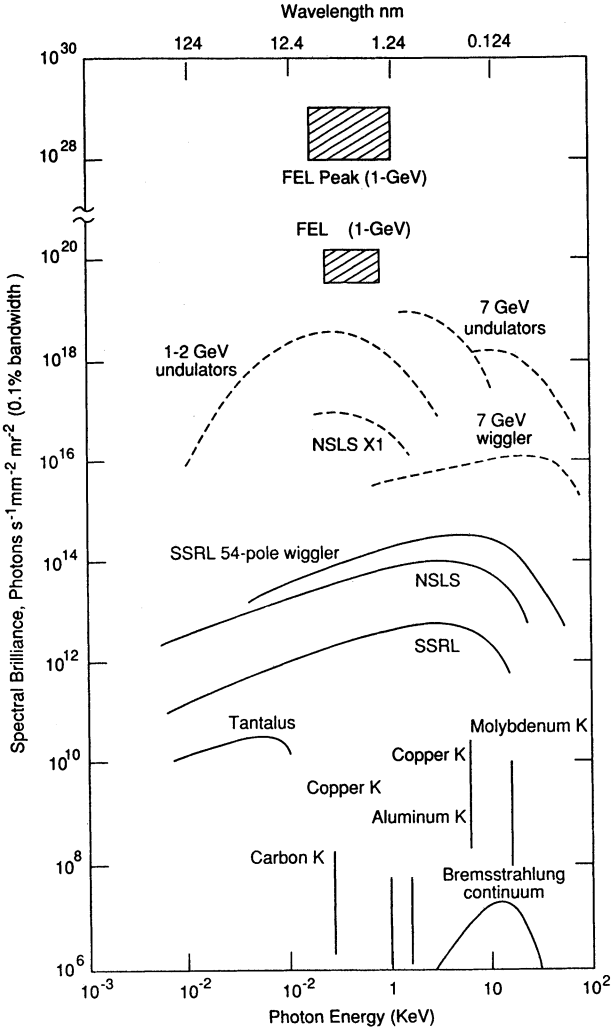

Figure 4.

Progress has also been made in the production of small emittance, large brilliance beams from electron guns, making the linac a possible option. Very good results have been obtained using large (30 to 100 MV/m) accelerating fields on the cathode, and laser driven photocathodes for picosecond pulses, or longer pulses followed by magnetic compression to reduce space charge effects at low beam energy(67,68,69). As an example, the Los Alamos gun, operating at about 1.3

GHz, with a Cs_3Sb cathode, and a field on it of 30 MV/m, has produced a beam with a normalized rms emittance of about 0.5 mm mrad, and a longitudinal brilliance of 2000A.

5. CONCLUSIONS

The recent progress in the production of high quality electron beams, using either storage rings or electron guns and linacs, gives us confidence that it will be possible , during the next few years, to produce beams with characteristics adequate to drive an FEL in the few nm region. This would provide a new source with peak power and photon brilliance far in excess of any existing source, as shown in Fig. 4, taken from ref. 58.

In other areas, as IR or high power systems to drive accelerators, much has already been accomplished and applications are already starting. New designs for undulators and the development of compact accelerator might make the FEL smaller and less expensive, and thus widen its availability to many laboratories and universities. New types of FELs, as for instance the gas-loaded FEL, will continue to be developed. We also expect, and need, to learn more about some aspects of the FEL physics, like optical guiding, superradiance, harmonic generation, quantum effects and coherence properties, which are essential for the development of the FEL in new regions.

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