GENERATION OF INTENSE XVUV PULSES WITH AN OPTICAL KLYSTRON ENHANCED SELF- AMPLIFIED SPONTANEOUS EMISSION FREE ELECTRON LASER

G. Penco # 1, E. Allaria[1], G. De Ninno[1], E. Ferrari[1,2], L. Giannessi[1,3]
[1]Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, Italy
[2]Università Degli Studi di Trieste, Dipartimento di Fisica (Trieste), Italy
[3]ENEA C.R. Frascati, Frascati (Roma), Italy

Abstract

Fermi is a seeded FEL operating in high-gain harmonic generation mode. The FEL layout is constituted by a modulator and six radiators separated by a dispersive section. The modulator and the radiators can be tuned to the same resonant frequency to set up an asymmetric optical klystron configuration where self-amplified spontaneous emission can be generated and studied. This paper presents the experiment consisting in the analysis of the enhancement of the self-amplified spontaneous emission (SASE) radiation by the dispersion in the optical klystron. The FEL pulses produced with the optical klystron configuration are several orders of magnitude more intense than in pure SASE mode with the dispersion set to zero. The experimental observations are in good agreement with simulation results and theoretical expectations. A comparison with the typical high-gain harmonic generation seeded FEL operation is also provided.

INTRODUCTION

The optical klystron (OK) concept was proposed by Vinokurov and Skrinsky in 1977 [1] to enhance the gain of a multi-pass free electron laser (FEL) driven by a storage ring. The basic scheme consists of two undulators separated by a dispersive section, which converts the beam energy modulation produced in the first undulator in density modulation, enhancing the electron bunching at the radiation wavelength and speeding up the FEL process in the second undulator. The first experimental demonstration of the optical klystron FEL was performed in 1979 at the VEPP-3 storage ring of the Budker Institute of Nuclear Physics (BINP, Novosibirsk, Russia) [2], obtaining an initial gain of 0.5% at 630 nm and improving it subsequently up to 2.5% per pass [3]. Afterwards, other FEL oscillator facilities implemented the optical klystron scheme, such as ACO SR FEL (LURE, France), which lased at 635 nm in 1983 [4] and at 463 nm in 1987 [5]. Improvements in the optical cavity mirror coatings made it possible to lase in the ultra-violet at 240 nm in 1989 (OK-4/VEPP-3 storage ring FEL [6]) and step by step down to 193 nm in 1999 (OK-4 Duke SR FEL [7]). In 2000, the ELETTRA storage ring FEL lased at 217.9 nm [8].

The gain of the optical klystron dramatically decreases with decreasing wavelength, while the optical cavity mirrors losses increase, and this has constituted a strong constrain in reaching emission at shorter wavelengths. A distributed optical klystron (DOK) was proposed by Litvinenko [9] to increase the gain and the first successful experiment was conducted in the DOK-1 FEL, at Duke University [10], obtaining a gain of about 48% per pass.

The progress of linac technologies has allowed generating very high brightness electron beams, able to drive single-pass high-gain FELs, providing intense radiation in the XVUV [11-13] and in the X-ray regimes [14,15]. A very common high -gain FEL mode is the self-amplified spontaneous emission (SASE) FEL, that is based on driving a high brightness electron beam through a long undulator tuned at a predetermined wavelength λ_r. The initially incoherent spontaneous radiation emitted by the beam couples with the electron beam itself and is then exponentially amplified, developing energy and density modulation at the wavelength λ_r, and finally emitting intense and coherent radiation. However, to reach the FEL intensity saturation in the extreme VUV and in the X-ray, it is necessary to have a long undulator chain, typically in the order of ~100 m, so alternative schemes have been studied in the past years in order to speed up the amplification process. In the following section we provide a short review of the 1-D theory describing the application of the OK concept to the SASE FEL.

OPTICAL KLYSTRON SASE FEL 1-D THEORY

The possibility to apply the optical klystron concept to high-gain FEL amplifiers has been faced in several papers [16-23]. An important result of these studies is that the klystron high-gain FEL performance is strongly influenced by the electron beam relative uncorrelated energy spread (δ), that is required to be much lower than the FEL Pierce parameter ρ [24,25]. In the following we briefly recall the 1-D theory developed in [20,23] that provides an approximated expression for the gain factor G of the optical klystron relative to the "pure" SASE mode, i.e. dispersive section turned off.

We consider an undulator resonating at the frequency $\omega_r = 2\pi/\lambda_r$. The optical klystron enhancement factor to the radiation electric field E at the scaled frequency $\nu=\omega/\omega_r$ can be written as follows:

$$R(\nu) = \frac{E_\nu^{OK}}{E_\nu^{noOK}} = \frac{1 - \int d\xi \dfrac{dV(\xi)}{(\mu-\xi)^2 d\xi} e^{-i\rho k_r R_{56}\xi} e^{ik_r \nu R_{56}/2}}{1 + 2\int d\xi \dfrac{V(\xi)}{(\mu-\xi)^3}} \tag{1}$$

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where $\xi=\delta/\rho$, μ is the complex growth rate of the radiation field in each undulator and $V(\xi)$ is the normalized energy distribution of the electron bunch. Integrating the enhancement factor $R(\nu)$ over the SASE spectrum $S(\nu)$ one can obtain the OK power gain factor G as:

$$G=\int d\nu \left|R(\nu)\right|^2 S(\nu) \tag{2}$$

Assuming a Gaussian SASE spectrum having a rms bandwidth equal to ρ, and considering $\sigma_\xi << 1$, the gain factor G can be well approximated by the following equation:

$$G\approx\frac{1}{9}\left[5+D^2e^{-D^2\sigma_\xi^2}+2\sqrt{3}De^{-\frac{D^2\sigma_\xi^2}{2}}+\left(\left(4+\sqrt{3}D\right)e^{-\frac{D^2\sigma_\xi^2}{2}}\cos\left(\frac{D}{2\rho}\right)-De^{-\frac{D^2\sigma_\xi^2}{2}}\sin\left(\frac{D}{2\rho}\right)\right)e^{-\frac{D^2\sigma_\xi^2}{8\rho^2}}\right] \tag{3}$$

where $D=k_r R_{56}\rho$.

When the dispersive section R_{56} is low, the chicane works as a phase shifter and the effect of the OK on FEL gain is mainly interferential.

By further increasing the chicane strength, the microbunching induced by the OK dominates and the gain factor G increases progressively up to the maximum FEL intensity, that occurs when $k_r R_{56}\sigma_\delta \sim 1$.

Since $\sigma_\delta << \rho$, when the R_{56} is close to the optimum value, D is much larger than 1 so that eq. (3) reduces to:

$$G\approx\frac{1}{9}\left(5+D^2e^{-D^2\sigma_\xi^2}+2\sqrt{3}De^{-\frac{D^2\sigma_\xi^2}{2}}\right) \tag{4}$$

OK-FEL DEMONSTRATION AT FERMI

FERMI is a single-pass S-band linac-driven FEL, based on the High Gain Harmonic Generation (HGHG) principle [26] and operating in the XVUV range (100 – 4 nm) [12,13]. In this scheme an external laser modulates in energy the electron beam passing in an undulator, called modulator, and a subsequent dispersive section converts this energy modulation in density modulation. The beam is then driven in an undulator chain, called radiator, tuned at a higher harmonic of the initial seed laser frequency, emitting coherent and intense radiation.

Nevertheless, by turning off the seed laser, the FERMI layout, and in particular the FEL-1 line (see Fig.1) has been found to be very suitable to realize an optical klystron in a high-gain FEL, by simply tuning both the modulator and the radiators at the same wavelength and exploiting the dispersive section to enhance the bunching induced by the spontaneous emission produced in the modulator. The wavelength tuning for both modulator and radiators is realized by changing the undulator gap [27,28].

As mentioned in the previous section, the ratio between the relative slice energy spread of the electron beam and the ρ parameter strongly affect the OK-FEL performance. The nominal FERMI electron beam has a very small δ, typically in the order of 10^{-4}, while the ρ parameter is more than one order of magnitude larger than δ for the usual wavelengths of operation (λ>10nm).

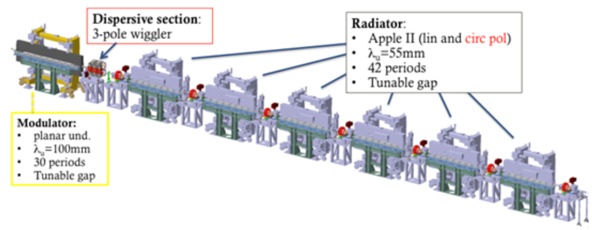

Figure 1: FERMI FEL-1 layout, including the modulator, the dispersive section and the six radiators.

In our experiment, we used a 1.058 GeV-500A electron beam, with a slice energy spread of about 90 keV (rms) and a normalized emittance of about 1.2 mm mrad. Both modulator and radiators have been tuned at 43 nm (the latter in circular polarization) and without activating the dispersive section, i.e. R_{56}=0 µm, the FEL energy per pulse was measured to be only few micro-Joules ("pure" SASE mode). Then, the dispersive section R_{56} has been progressively increased, while detecting the output FEL intensity. The experimental results are reported in Fig. 2: the radiation intensity has been enhanced by more than an order of magnitude with respect to the "pure" SASE. A more detailed post-processing analysis will be provided in a paper ready to be published [29].

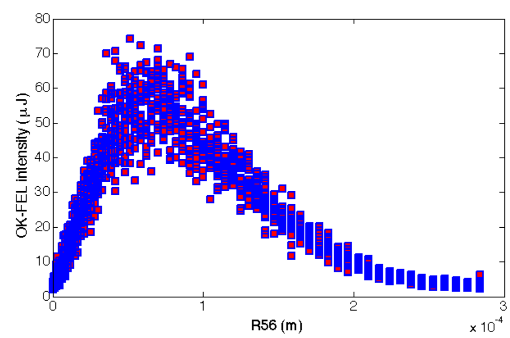

Figure 2: OK-FEL intensity versus the chicane R_{56}.

BEAM SLICE ENERGY SPREAD CONTROL

Since the beam slice energy spread is so important for the efficiency of the OK-FEL, we have modified it by acting on the laser heater system [30-31]. The latter is installed at the end of the linac injector [32], at about 100 MeV, and it is routinely exploited to slightly increase the very small natural intrinsic energy spread at the gun (typically in the order of 3-5 keV [33]) in order to suppress the microbunching instabilities driven by collective effects, such as coherent synchrotron radiation in the magnetic bunch compressor [34] and space charge effects along the linac [35]. The theoretical induced uncorrelated energy spread as a function of the laser heater intensity for the nominal 500 pC FERMI electron bunch has been calculated and is plotted in Figure 3.

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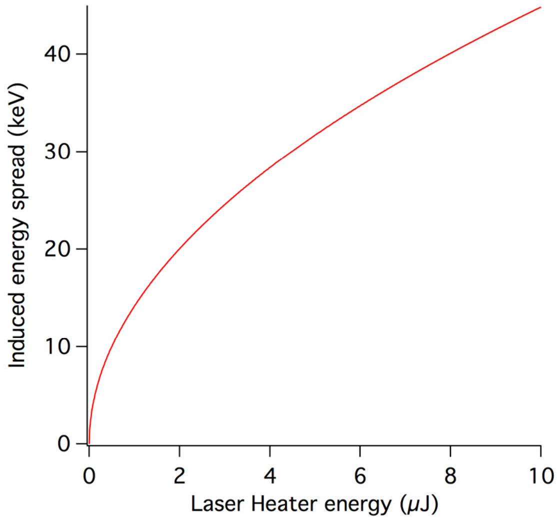

Figure 3: Induced slice energy spread versus laser heater intensity calculated for a 97 MeV electron bunch, with a transverse spot size of 0.1 mm, assuming a 0.2 mm laser heater transverse spot size in the overlapping region.

Figure 4 shows the typical measured slice energy spread at the end of the linac [36] as a function of the laser heater intensity, after the electron beam is compressed by almost a factor 10 to obtain a peak current of 500A. One can observe that increasing the laser heater intensity from 0 to about 1 μJ leads to a decrease of the slice energy spread at the end of the linac thanks to the efficient microbunching suppression, down to a minimum value of about 85 keV. However for larger laser heater intensities, the larger induced energy spread at the injector is translated in an increment of the slice energy spread at the end of the linac.

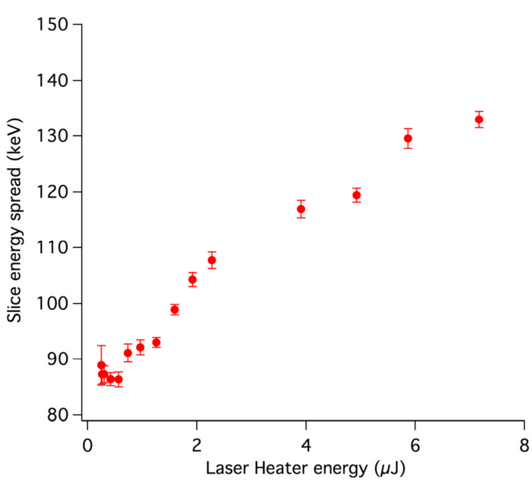

Figure 4: Uncorrelated energy spread versus laser heater intensity measured at the end of the linac by using a transverse deflecting cavity coupled with an electron energy spectrometer.

We have repeated the measurements of the OK-FEL intensity as a function of the dispersive section R_{56} for different value of the laser heater energy, i.e. for different values of the induced slice energy spread. For higher laser heater energy, the larger induced energy spread depletes the optical klystron FEL gain and as expected its maximum value is obtained for smaller values of R_{56}. In particular increasing the uncorrelated energy spread from about 90 keV to 120 keV reduced the maximum OK-FEL intensity by about a factor 2 [29].

We have then fitted the aforementioned experimental behaviour of the OK-FEL versus R_{56} with the theoretical factor gain curve of eq. (4). A good agreement has been observed for value of the R_{56} smaller or close to the optimum value, while for larger R_{56} the measured OK-FEL intensity is larger than expected by the 1-D theory. The latter in fact makes the strong assumption that electrons have a constant Gaussian slice energy distribution along the bunch while the real bunch presents a non-uniform longitudinal phase space [36]. Even when the laser heater is tuned to optimize the OK-FEL performance, residual microbunching structures are anyway present and can give some contributions to the enhancement of the optical klystron also for large value of R_{56}. A more detailed analysis of the experimental results is going to be provided in a subsequent paper [29].

We have exploited the optical klystron setup to enhance the SASE also at 32.4 nm and at 20 nm, obtaining a gain factor of about 20 and 10 respectively (with proper tuning of the dispersive section).

We have measured the gain curve of the OK-FEL operating at 32.4 nm by progressively opening the radiators gap for three different value of the dispersive section R_{56}. The OK-FEL gain length measured in each case is listed in Table 1.

Table 1: OK-FEL Gain Length at 32.4 nm as Measured for Three Values of the Chicane R_{56}

Chicane R_{56} (μm)	**Gain Length (m)**
16	1.16 ± 0.03
26	1.19 ± 0.03
63	1.23 ± 0.02

OK-FEL GAIN LENGTH

We have simulated the experiment conducted on FEL-1 at 32.4 nm with GENESIS 1.3 [37] comparing the optical klystron case with the "pure" SASE; the results are plotted in Figure 5.

The optical klystron does not change the FEL gain length that is very similar to the "pure" SASE mode, but it speeds up the process: the bunching induced after the dispersive section enhances the radiation after the first radiator (z=2.3m) by almost two orders of magnitude. The total saturation length could be therefore reduced by about 20%.

As expected the OK-FEL gain length, see Table 1, is independent from the chicane R56 and the results are in very good agreement with the GENESIS simulations.

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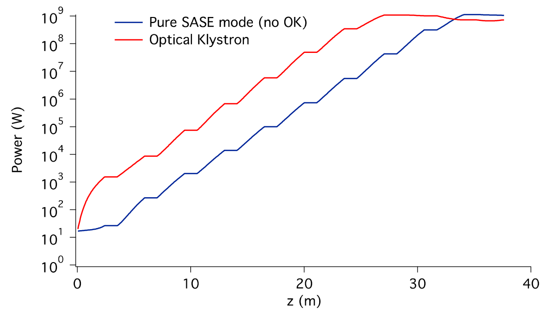

Figure 5: GENESIS simulations results of the FEL power gain curve at 32.4 nm for the OK-FEL and the "pure" SASE mode. The starting point (z=0) corresponds to the exit of the dispersive section.

CONCLUSION

The optical klystron enhancement to SASE FEL has been experimentally demonstrated at FERMI down to 20 nm on FEL-1 and at 12 nm on FEL-2. Our experiments have confirmed that the Optical Klystron FEL performance is strongly influenced by the electron beam relative uncorrelated energy spread, that must be much smaller than the FEL ρ parameter.

1-D theory present in literature can reproduce the experimental results when microbunching structures in the longitudinal phase space are fully suppressed and the intrinsic energy spread is similar to the "FEL-slice" energy spread. Otherwise, it would be better to include the non-uniformity of the longitudinal phase space and distinguish between the intrinsic uncorrelated energy spread on the radiation wavelength λ_r scale and the energy spread on the FEL cooperation length scale.

Measurements of the OK-FEL gain curve have confirmed that the gain length is independent on the dispersive section as expected by simulations.

FERMI has been demonstrated to be able to operate also in SASE mode by taking advantage of the optical klystron setup: with this scheme it is capable to provide several tens of μJ in XVUV wavelength range.

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