THE FREE ELECTRON LASER KLYSTRON AMPLIFIER CONCEPT

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Abstract

We consider optical klystron with a high gain per cascade pass. In order to achieve high gain at short wavelengths, conventional FEL amplifiers require electron beam peak current of a few kA. This is achieved by applying longitudinal compression using a magnetic chicane. In the case of klystron things are quite different and gain of klystron does not depend on the bunch compression in the injector linac. A distinguishing feature of the klystron amplifier is that maximum of gain per cascade pass at high beam peak current is the same as at low beam peak current without compression. Second important feature of the klystron configuration is that there are no requirements on the alignment of the cascade undulators and dispersion sections. This is related to the fact that the cascades, in our (high gain) case, do not need the radiation phase matching. There are applications, like XFELs, where unique properties of high gain klystron FEL amplifier are very desirable. Such a scheme allows one to decrease the total length of magnetic system. On the other hand, the saturation efficiency of the klystron is the same as that of conventional XFEL.

INTRODUCTION

High gain FEL amplifiers are of interest for a variety of potential applications that range from X-ray lasers [1, 2] to ultraviolet MW-scale industrial lasers [3]. There are various versions of the high gain FEL amplifier. A number of high gain FEL amplifier concepts may prove useful for XFEL applications. Two especially noteworthy ones are the FEL amplifier with a single uniform undulator [1, 2] and the distributed optical klystron [4, 5, 6, 7]. The high gain cascade klystron amplifier described in this paper is an attractive alternative to other configurations for operation in the X-ray wavelength range (see Fig. 1).

Electron bunches with very small transverse emittance and high peak current are needed for the operation of conventional XFELs. This is achieved using a two-step strategy: first generate beams with small transverse emittance using an RF photocathode and, second, apply longitudinal compression at high energy using a magnetic chicane. Although simple in first-order theory, the physics of bunch compression becomes very challenging if collective effects like space charge forces and coherent synchrotron radiation forces (CSR) are taken into account. Self-fields of bunches as short as 10-100 μm have never been measured and are challenging to predict.

The situation is quite different for klystron amplifier scheme described in our paper. A distinguishing feature of the klystron amplifier is the absence of apparent limitations which would prevent operation without bunch compression in the injector linac. As we will see, the gain per cascade pass is proportional to the peak current and inversely proportional to the energy spread of the beam. Since the bunch length and energy spread are related to each other through Liouville's theorem, the peak current and energy spread cannot vary independently of each other in the injector linac. To extent that local energy spead is proportional to the peak current, which is usually the case for bunch compression, the gain will be independent of the actual peak current. We see, therefore, that klystron gain in linear regime depends only on the actual photoinjector parameters. This incipient proportionality between gain and I_0/σ_{γ} (I_0 is a current and σ_{γ} is a local energy spread in units of the rest electron energy) is a temptation, in designing an XFEL, to go to very high values of I_0/σ_γ and very long values of bunch length. Starting with this safe scenario, one may gradually increase compression factor getting shorter FEL pulses with higher peak power (brilliance). Note that the average power (brilliance) is almost independent of the compression factor. It is also worth mentioning that there is a possibility [8] to get short (10 fs) radiation pulses for the pump-probe experiments, having long (10 ps) electron bunches. To illustrate further possible advantages of the klystron amplifier, we describe a multi-user facility having a ring geometry, and thus being similar to the 3rd generation synchrotron radiation facilities.

THE GAIN OF A KLYSTRON AMPLIFIER

A detailed theoretical analysis of a klystron amplifier with a high gain per cascade can be found in [8]. Here we present some results of that analysis.

The principle of klystron operation is simple and is very similar to that of a multi-resonator microwave klystron. A modulated electron beam radiates in a first undulator, and the radiation modulates the beam in energy. Then the beam passes a dispersion section where the energy modulation is converted into the density modulation which is much higher than the original one. In the second undulator the beam with the enhanced density modulation radiates pro-



Figure 1: Schematic diagram of high gain cascade klystron amplifier

ducing much higher energy modulation etc. The process can continue in several cascades up to saturation in the last (output) undulator. Since the gain per cascade is high, the phase matching (on the scale of the radiation wavelength) between the beam and the radiation is obviously not required. An initial signal for such a device in VUV and X-ray spectral range is the shot noise in electron beam.

We present here the expressions for a gain per cascade for two different regimes of the klystron amplifier operation. In the first case the geometrical emittance of the electron beam ϵ is small as compared to $\lambda/(2\pi)$, where λ is the resonant wavelength. In this case the beta-function in the undulators can be chosen in such a way that the diffraction parameter, $2\pi\sigma^2/(\lambda L_w)$, is small (here σ is transverse size of the beam and L_w is the length of an undulator segment). At the same time the effect of velocity spread due to emittance on FEL operation can be neglected. After optimization of the strength of the dispersion section one gets the amplitude gain per cascade [8]:

$$G_0 \simeq 4 \frac{A_{\rm JJ}^2 K^2}{(1+K^2)} \frac{N_{\rm w} I_0}{\sigma_{\gamma} I_{\rm A}} , \qquad (1)$$

where K is the rms undulator parameter, $N_{\rm w}$ is the number of undulator periods per an undulator, $I_{\rm A} = 17$ kA is the Alfven current, $A_{\rm JJ} = 1$ for a helical undulator and

$$A_{\rm JJ} = [J_0(Q) - J_1(Q)]$$

for a planar undulator. Here $Q = K^2/(2 + 2K^2)$ and $J_n(Q)$ is a Bessel function of *n*th order.

In the opposite limit, $2\pi\epsilon/\lambda \gg 1$, after optimizing betafunction and the strength of dispersion section one gets:

$$G_0 \simeq 2 \frac{A_{\rm JJ}^2 K^2}{(1+K^2)} \frac{N_{\rm w} I_0}{\sigma_\gamma I_{\rm A}} \left(\frac{\lambda}{2\pi\epsilon}\right)^2 \,. \tag{2}$$

In the latter case the diffraction parameter is big, and the velocity spread due to emittance should be carefully taken into account. Note that in contrast with a conventional SASE, the effects of emittance and energy spread on longitudinal dynamics are separated in a klystron amplifier: emittance (energy spread) is important in undulators (dispersion sections). The noticeable feature of the results (1) and (2) is that the gain depends on the ratio I_0/σ_{γ} and is, therefore, independent of compression factor in the beam formation system. It is also interesting to note that in the case of a small emittance the gain is defined by the longitudinal brightness of the electron beam, while for a large emittance - by total brightness (particles density in 6-D phase space).

Let us present an example for the case when the emittance is below diffraction limit and the undulator is planar. With the numerical values $\lambda_{\rm w} = 3$ cm, K = 1, $\gamma = 10^3$, the resonance value of wavelength is $\lambda = 30$ nm. If the number of the undulator period is $N_{\rm w} = 100$, normalized transverse emittance $\epsilon_n = 2\mu m$, and betatron function is equal to the undulator length, the diffraction parameter is about 0.4. For a peak current of 100 A and a local energy spread of 5 keV, appropriate substitution in (1) shows that the gain per cascade pass is about $G_0 \simeq 10^2$ (or, intensity gain $G_0^2 \simeq 10^4$). In order to reach saturation in a klystron amplifier, starting up from the shot noise, the total intensity gain should be of the order $N_{\lambda}N_{\rm w}$ [8], where N_{λ} is the number of electrons per radiation wavelength. Thus, for the considered set of parameters, one needs two cascades of amplification and the output undulator as shown in Fig. 1.



Figure 2: Diagram of a possible fourth-generation synchrotron facility using free-electron laser klystron amplifiers



Figure 3: Electron ring cell design. Using a klystron electromagnetic dispersion section as a switching element it is possible to quickly switch off (on) the cell klystron amplifier thus providing multi-user capability. This design makes it possible to make various wavelengths available in the XFEL laboratory quasi-simultaneously

MULTI-USER DISTRIBUTION SYSTEM FOR XFEL LABORATORY

An X-ray laboratory should serve several, may be up to ten experimental stations which can be operated independently according to the needs of the user community. On the other hand, the multi-user distribution system has to satisfy an additional requirement. Passing the electron bunch through the bending magnets must avoid emittance dilution due to coherent synchrotron radiation (CSR) effects. For very short bunches and very high peak current, CSR can generate energy spread in the bending magnets and thus dilute the horizontal emittance. As a result, the preferred layout of a conventional SASE FEL is a linear arrangement in which the injector, accelerator, bunch compressors and undulators are nearly collinear, and in which the electron beam does not change direction between accelerator and undulators.

The situation is quite different for the klystron amplifier scheme proposed in our paper. Since it operates without bunch compression in the injector linac, the problem of emittance dilution in the bending magnets does not exist. An electron beam distribution system based on uncompressed electron beam can provide efficient ways to generate a multi-user facility - very similar to present day synchrotron radiation facilities. A possible layout of a soft X-ray FEL laboratory based on an electron ring distribution system is shown in Fig. 2. The layout of the laboratory follows a similar approach as that used for synchrotron light sources. The FEL user facility consists of an injector linac and electron beam distribution system. The injector is composed of a RF gun with photocathode and a main (superconducting) linac. In order to make efficient use of the new source it is proposed to segment the full circumference of a distribution system into arcs which are repeated a number of times to form a complete ring. Each cell includes a two-cascade klystron and a bending magnet. A specific realization of the electron ring cell is sketched in Fig. 3. The electron beam transport line guiding electrons from the injector linac to the experimental hall is connected tangentially to one of the straight sections of the electron ring. In order to obtain a useful separation between the experimental areas behind the photon beam lines, an angle of 36 degrees between two neighboring lines would be desirable. Thus, ten beam lines can be installed on a complete electron ring. Using klystron (electromagnetic) dispersion sections in each cell as switching elements it is possible to quickly switch the FEL photon beam from one experiment to the other, thus providing multi-user capability. Users can define the radiation wavelength for their experiment independently of each other to a very large extent, since they use different undulators. Injector linac and electron beam transport lines operate at fixed parameters. At a fixed electron energy the magnet gap of the klystron undulators can be varied mechanically for wavelength tuning. This design makes it possible to make various wavelengths available in the XFEL laboratory quasi-simultaneously. It is a great advantage that injector and electron beam transport lines in the new scheme of multi-user facility operate at fixed parameters and that an "electron switchyard" is not required.

When a relativistic electron beam passes through the undulator, it emits incoherent radiation. This process leads to an increase of the energy spread in the beam due to quantum fluctuations of the undulator radiation. This effect grows significantly with an increase in electron beam energy, strength field and length of the undulator. This effect should be carefully taken into account when designing multi-user distribution system. The expression for the rate of energy diffusion can be found in [9]. The next numerical example illustrates the amplitude of the effect. If $\gamma = 10^3$, K = 1, $\lambda_w = 3$ cm, and the total length of the undulator system is equal to 100 m, then the energy spread increase due to quantum fluctuations is about 1 keV at the end of the 10th klystron amplifier, and has a negligible effect on the klystron performance.

CONCLUSION

The high-gain klystron amplifier described in this paper is an attractive alternative to other FEL configurations for operation in short wavelength range. A distinguishing feature of the klystron amplifier, operating in the VUV and soft X-ray range, is the absence of apparent limitations which would prevent operation without bunch compression in the injector linac. The scheme can also be adapted for generation of hard X-ray radiation. In this case one should take into account quantum diffusion in the undulator. A consequence would be that some moderate compression would be needed (which could still be more safe than the agressive compression required for conventional SASE FELs [1, 2]).

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