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CONCEPT OF HIGH-POWER CW IR-THz SOURCE FOR THE RADIATION SOURCE ELBE UPGRADE

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Abstract

The Radiation Source ELBE at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) is a user facility based on a 1 mA - 40 MeV CW SRF LINAC. Presently HZDR is considering upgrade options for the ELBE or its replacement with a new CW, SRF LINAC-based user facility. A part of the user requirements is the capability to generate IR and THz pulse in the frequency range from 0.1 through 30 THz, with pulse energies in the range from 100 μJ through a few mJ, at the repetition rate between 100 kHz and 1 MHz. This corresponds to the pulse energy increase, dependent on the wavelength, by a factor from 100 through 1000. In this contribution, we outline key aspects of a concept, which would allow to achieve such parameters. These aspects are: 1 - use of a beam with longitudinal density modulation and bunching factor of about 0.5 at the fundamental frequency; 2 - achieving the density modulation through the mechanism similar to the one used in optical klystron (OK); 3 – generating the necessary for the modulation optical beam by an FEL oscillator, and 4 - using two electron injectors. First injector would provide a beam for the FEL oscillator. Second high charge injector would provide the beam for the high pulse energy generation for users. All-in-all the concept of the new radiation source is very similar to an OK, but operating with two beams simultaneously.

INTRODUCTION

To achieve the very high pulse energies of few hundred μJ, at the above-mentioned repetition rates a new configuration of the photon source is proposed. To our knowledge other existing electron beam-based photon generation schemes cannot provide the required combination of the high pulse energy and repetition rate. In the scheme proposed here an electron beam with a longitudinally modulated density will be used to generate coherent undulator radiation. It is suggested to achieve the necessary longitudinal density modulation of the electron beam with the help of a scheme similar to the one used in Optical Klystron FEL OK [1]. Operation of such a photon source will require the seeding, i.e., energy modulating optical beam, tunable, essentially, in the whole frequency range of the source - 0.1 to 30 THz, with sufficiently high peak power. With suggest, that such sources can be realized as an FEL oscillator. Moreover, it is proposed that the intra-cavity optical pulse of the oscillator should be used for the energy modulation of the electron beam. This will allow to significantly relax the requirements on the oscillator and on the electron beam, required to drive it. The required FEL oscillator can be operated with the electron beam with the bunch charge less than 100 pC. To keep the optical resonator length easily manageable, the oscillator can be operated with the bunch frequency of about 10 MHz. The combination of the 100 pC bunch charge and the repetition rate of the 10 MHz would require a CW accelerator system with average current of about 1 mA, which is comfortably within the ELBE's accelerator system capability.

To satisfy the requirements of the high IR-THz pulse energy, the beam with the bunch charge significantly higher, than the 100 pC necessary for the seeding oscillator, will necessary. It is suggested to operate such beam with the bunch charge approximately 10 times higher, i.e., at 1 nC, or higher, when allowed by electron gun technology. For higher reliability, easier tuning and optimization of such a radiation source, it is proposed that the 100 pC beam and 1 nC beam should be generated by two separate electron sources. The repetition rate of high bunch charge beam can be as high as 1 MHz. The minimal repetition frequency of the high charge beam can be arbitrary low, with the only condition that it must be a sub-harmonic of the repetition frequency of the beam in the FEL oscillator-modulator.

The undulator based source will provide a relatively narrowband – multicycle radiation pulses. In parallel to such a source, the new facility would also have a broadband few-cycle THz sources. These sources will be based either on a coherent diffraction radiation CDR, coherent synchrotron radiation (CSR) or coherent edge radiation (CER) from a dipole magnet. To provide high pulse energy this source would be operated by the beam from the high bunch charge electron gun. The continuous pulse train, from the high bunch charge electron gun, can be split into few beams with the help of an RF separator. The different beams, downstream of the RF separator would be used to drive different sources simultaneously.

SUPERRADIANT UNDULATOR WITH STRONGLY COMPRESSED BUNCH

The intensity of coherent undulator radiation, as of any other coherent radiation mechanism, can be expressed as $I_c(\omega) = I_c(\omega)\, N_e^2\, |f_b(\omega)|^2$, where $I_0(\omega)$ is the undulator radiation intensity from a single electron, N_e is the number of the electrons in the bunch, and $f_b(\omega)$ is the Fourier transform of the longitudinal bunch distribution also called bunching factor. Since the coherent radiation intensity dependence on the bunch charge is quadratic, a part of the new facility design direction is to use the bunch charge as high as practical for a CW accelerator system.

To understand the concept proposed here and our design choices, it is helpful to consider, first, the coherent

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undulator radiation output from a strongly compressed bunch. It can be shown that the maximum spectral brightness of the undulator radiation is achieved at first harmonic $n = 1$ and with the undulator parameter K = 1 [2, 3]. Figure 1 shows the calculated pulse energy from an undulator assuming, $n = 1$ (first harmonic), $K = 1$, undulator period $\lambda_u = 30$ cm, and number of undulator period $N_u = 17$. The calculation also assumes bunch charge of 1 nC. Four cases are shown in Fig. 1. First case, shown as black line, corresponds to the completely longitudinally coherent radiation, i.e., $f_b(\omega) = 1$, which is the upper limit of the undulator radiation intensity for the particular undulator with the bunch charge of 1 nC. Another two cases assume Gaussian longitudinal bunch distribution. To show the effect of the RMS bunch length on the coherent undulator radiation intensity, calculations made for bunch length of 0.2 ps and 1 ps RMS are shown by blue and green lines correspondently. To maximize the possible pulse energy, it is assumed, that the beam energy is adjusted for each wavelength such that the undulator parameter K is always equals to 1, which make this set of calculations optimistic. The bunch length of 0.2 ps is chosen for this example because estimations suggest that this could be the limit of bunch compression for a 1 nC bunch, when it is accelerated to the energy of 50 MeV and longitudinally compressed including removal of the linac's RF curvature to the second order. The calculations summarized in the Fig. 1 demonstrate that even in a somewhat optimistic case, a conventional coherent undulator source driven by a short bunch could provide pulses energies around 100 μJ only in the frequency range from 0.2 THz to about 1.5 THz.

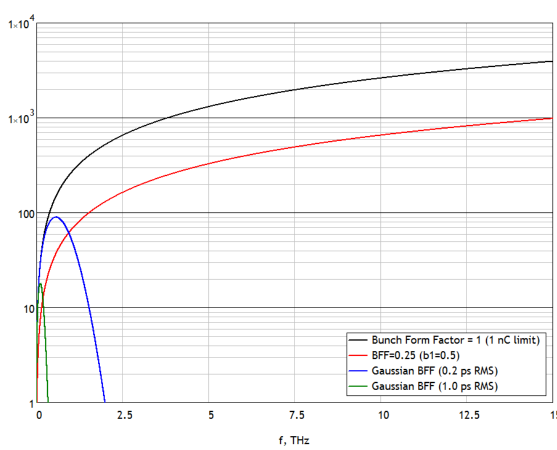

Figure 1: Coherent undulator radiation intensity.

LONGITUDINAL BEAM MODULATION

The main reason for the lower pulse energy of the coherent undulator source at frequencies higher than ~1.5 THz is the small longitudinal form factor of the bunch. One way to overcome the limitations of the bunching factor given by bunch compression is to use longitudinally modulated, with the periodicity of the desired radiation wavelength, beam. We argue, that with the requirement of the pulse repetition rate between 100 kHz and 1 MHz, the most suitable way to modulate the beam longitudinally on the scale from 10 μm through 250 μm is to use the mechanisms used in an OK or a laser heater. There, the longitudinal density modulation is obtained via the two-step process. First, the electron beam energy is modulated by co-propagating the electron beam together with an optical beam in an undulator. The mean beam energy, the wavelength of the external optical beam, the undulator period and its K parameter are arranged to satisfy the FEL resonant condition. This leads to the net energy exchange between the external optical mode and the electron beam with periodicity of the optical mode. In the seconds step, the energy modulated beam is passed through a beam transport section with longitudinal dispersion. This results in the modulation of the longitudinal density of the electron beam again with the periodicity of the external optical mode. The detailed description of this process can be found in [4] and its references. Here we only summarize results and list most relevant parameters. Linear 1D theory of the micro-bunching instability predicts the growth of the slice energy spread to ~ 50 keV for the 1 nC bunch when it is accelerated to 50 MeV. For the robustness of the concept, for now, we assume that the slice energy spread could grow to 200 keV. We also assume the capability to induce the energy modulation amplitude 3 times larger than the slice energy spread. Under such condition the bunching factor of ~ 0.5 at first harmonic can be achieved. The energy change of an electron co-propagating with an optical mode in undulator is given by, $\Delta E_m = -e \cdot \mathcal{E}_{\hbar\omega} \cdot K \cdot L_{mod}\, cos(\varphi)/2\gamma$, where e is the electron charge, $\mathcal{E}_{\hbar\omega}$ is the amplitude of the modulating optical mode electrical field, L_{mod} is the length of the undulator-modulator, and φ is the phase of the optical mode corresponding to the longitudinal position of the electron. Assuming $L_{mod} = 1$ m and maximum beam energy of 50 MeV we get the required amplitude of the optical mode to be ~ 40 MV/m. Assuming radius of the mode of 1.5 mm, and 1 ps pulse length, the mode with the amplitude of 40 MV/m would correspond to pulse energy of $\mathbb{E}_p = \left(\mathcal{E}_{\hbar\omega}{}^2 c\varepsilon_0\, \pi r^2\, \Delta t\right)/2$ about 15 μJ.

FEL OSCILLATOR AS ENERGY MODULATOR

FEL modelling based on the set of Dattoli's analytical formulas [5], aided by empirical correction factors introduced by S. Benson [6], predicts that a very high performance FEL oscillator could provide the necessary amplitude of the optical mode in the outcoupled pulse.

On the other hand, an FEL oscillator can easily provide the necessary electrical field amplitude, when its intracavity optical pulse is used. In this case the outcoupling from the resonator can be minimized, so that only a very small fraction of the intra-cavity power, necessary for the FEL system monitoring and diagnostics, is outcoupled. The FEL oscillator modelling, which assumes the use of an undulator with period of 100 mm and 40 periods, and an electron beam parameters as presently used at ELBE: bunch charge of 77 pC, the RMS pulse length of 0.5 ps, longitudinal emittance of 50 keV·ps, and transverse

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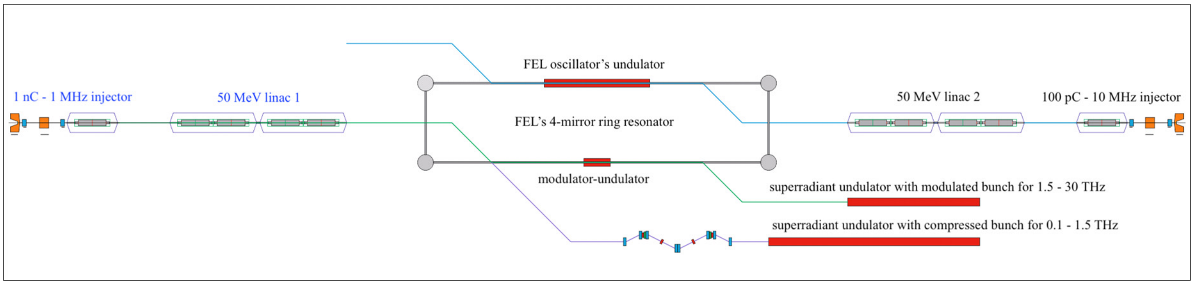

Figure 2: Layout option of the two-beam optical klystron IR-THz source utilizing two separate electron sources and two separate linacs for 1 nC beam with repetition rate of 1 MHz and 100 pC beam with the repetition rate of 10 MHz.

normalized emittance in both planes of 10 mm·mrad, and Rayleigh length of the optical resonator of 1 m, show that for any wavelength, in the required range, the intra-cavity pulse can provide electrical fields of, at least, five times higher than the required one.

The optical resonator of the oscillator can be implemented as a ring resonator. On the ring resonator two different undulators would be installed. A longer undulator would be used with the low charge - high repetition rate beam to generate and maintain the optical beam. The shorter undulator installed on the return pass of the resonator would be used for the energy modulation of the high charge. The two electron beams would be transported in two separate, completely independent beamlines. The advantage of such configuration is that it adds two additional degrees of freedom to the system. One is the freedom to choose the modulator-undulator length. Another is the freedom to choose the transverse size of the optical mode in the modulator-undulator. While the modulator length can be chosen only once, the transverse size of the mode can be made adjustable in a completed system. This can be accomplished either by deformable mirrors, or using sets of exchangeable optics. Adjusting the transverse beam mode size would allow to adjust and control the modulation amplitude without any changes to the oscillator. It is reasonable to expect that the high bunch charge beam will have larger transverse emittance than the beam used to drive the oscillator, therefore its size, when matched to an undulator will be different as well. Then for an optimal interaction with the optical beam the transverse size of the optical beam might needs to be adjusted.

POSSIBLE SYSTEM LAYOUTS

Two layouts of the accelerator system can be considered. In both cases two electron sources are needed: one for the high bunch charge 1 nC beam at 1 MHz for the radiation generation, another for 100 pC beam at 10 MHz to drive the FEL oscillator. The use of ELBE linac modules with accelerating gradient of 12.5 MV/m is assumed, such that two modules can accelerate beam to 50 MeV. One possibility would be to use a single linac where the two beams are propagating in opposite directions during acceleration. The length of the LINAC section with adjacent beam optics systems can be made sufficiently short, so that the 1 MHz beam and 10 MHz beams, do not meet. The advantage of such configuration is cost saving on the SRF linac and the LHe cryo plant. Another layout option, shown in Fig. 2, uses two separate linacs. Such layout would have substantially simpler beam optics, and would allow much easier ways to organize multi-user operation. The injector and linac 2, shown on the right, are used to drive the FEL oscillator, which would be used for energy modulation of the high bunch charge, or for FEL user experiments similarly to present ELBE's FELs. The beam from injector and linac 1, shown on the left, could be used either with its maximum repetition rate of 1 MHz, or its fraction, to drive the superradiant undulator with modulated beam. In a similar fashion, this beam would be also used, after a strong non-linear compression, for with the second superradiant undulator for generation in the frequency range 0.1 through 1.5 THz. It would be possible to use both undulator sources simultaneously with repetition rate of up to 500 kHz. Since the bottom undulator source does not required energy modulation it is possible to use it and the FEL oscillator for independent user experiments at the same time. Besides the IR-THz sources it is foreseen to have electron beam driven positron source used for material research. This sources also requires high bunch charge with a repetition rate not higher that 1 MHz, therefore with be using the 1 nC-1MHz injector and linac. It will be possible to use this source simultaneously with superradiant undulators at repetition rate of few hundred kHz, splitting the 1 MHz beam with the help of RF beam separators.

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