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DESIGN 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. Such key 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) and HGHG FEL; 3 - generating necessary for the modulation optical beam by an FEL oscillator, and 4 - using two electron injectors, where one injector provides beam for the FEL oscillator while second high charge injector provides beam for the high energy per pulse generation for user experiments. 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, at the above-mentioned repetition rates a new configuration of the photon source is proposed. The new architecture is necessary since no other existing electron beam-based photon generation schemes can 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.

We suggest 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] or High Gain Harmonic Generation FEL [2]. Operation of such a photon source will require the modulating optical beam, tunable, essentially, in the whole frequency range of the source - 0.1 to 30 THz, with sufficient 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. It will be shown, in later section of this contribution, that the required FEL oscillator can be operated with the electron beam with the bunch charge of 100 pC. To keep the optical resonator length easily manageable for the facility, the oscillator can be operated with the bunch frequency of about 10 MHz. The combination of the bunch charge of 100 pC 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 capabilities of the accelerator system presently used at HZDR by the Radiation Source ELBE.

It can be shown, that to satisfy the requirements of the high pulse energy, the beam used for the IR-THz generation for user experiments will have to be operated with the bunch charge significantly higher than the 100 pC necessary for the seeding oscillator. 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. However, single SRF LINAC can be used to accelerate the two beams to the final beam energy. 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 subharmonic of the repetition frequency of the beam in the FEL oscillator-modulator.

The undulator based source will provide a relatively narrow-band multi-cycle radiation pulses. In parallel to such a source the new facility would also operate a broadband few-cycle THz source. This source will be based either on a coherent diffraction radiation CDR, or on the coherent synchrotron radiation (CSR) from a single bend magnet. To provide high pulse energy this source would be operated by the beam from the high bunch charge 1 nC electron gun. The continuous pulse train from the high bunch charge electron gun can be split in to two beams of equal repetition rate with the help of a resonant RF separator. One of these beams will be used for the pre-bunched super-radiant undulator source. The second beam from downstream of the RF separator will be compressed longitudinally in an optimal way to provide higher peak current and used to generate the few-cycle THz pulses.

SUPERRADIANT UNDULATOR SOURCE

The intensity of coherent undulator radiation, as of any other coherent radiation mechanism, can be expressed as

$$I_c(\omega) = I_c(\omega) \cdot N_e^2 \cdot |f_b(\omega)|^2 \qquad (1)$$

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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. The prominent feature of the coherent radiation intensity is its quadratic depends on the number of participating electrons, i.e., bunch charge. A part of the new facility design considerations is to increase the bunch charge as much as practical for a CW accelerator system.

To understand the concept of the facility proposed here and our design choices, it is helpful to consider, first, the coherent 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 [3, 4]. 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., $f_b(\omega) = 1$, and shows 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 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.

LONGITUDINAL BEAM MODULATION

The main reason for the low 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 improve the source peak intensity is to use the bunch charge as high as practical, while maintaining sufficiently small longitudinal emittance. Another way to increase the source peak intensity is to increase the longitudinal form factor of the beam. This can be achieved by introducing longitudinal density modulation of the beam with the periodicity of the desired radiation wavelength. 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 and in HGHG FEL. 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.

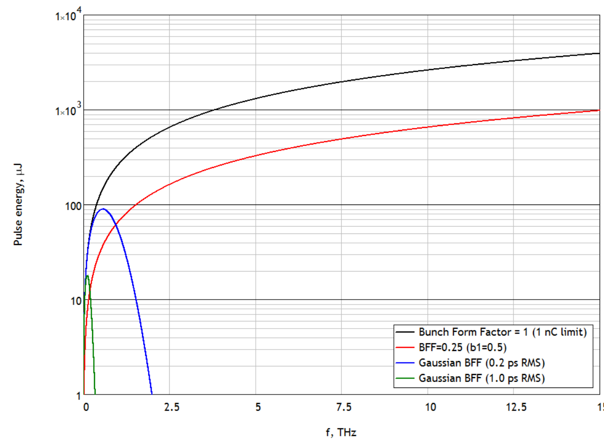

Figure 1: Coherent undulator radiation intensity.

The detailed theory of this process is described in [2] and its references. Here we only summarize results it its application 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, 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,

$$\Delta E_m = -e \cdot \mathcal{E}_{\hbar\omega} \cdot K \cdot L_{mod} \cos(\varphi)/2\gamma. \tag{2}$$

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.

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FEL OSCILLATOR AS SEED SOURCE

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.

At the same time, an FEL oscillator can easily provide the necessary electrical field amplitude, when its intra-cavity optical pulse is used. In this case the outcoupling from the resonator can be minimized, such that only a very small fraction of the intra-cavity power, necessary for the FEL system monitoring and diagnostics, is out-coupled. Fig. 2 shows the calculated electrical field strengths of the intra-cavity optical pulse. The calculation assumes the use of one of an undulator with period of 100 mm and 40 periods, and an electron beam similar to the one presently used at ELBE, with the bunch charge of 77 pC, the RMS pulse length of 0.5 ps, longitudinal emittance of 50 keV·ps, and transverse normalized RMS emittance in both planes of 10 mm·mrad. The Rayleigh length of the optical resonator of 1 m is assumed. The modelling results, depicted in Fig. 2, show that for any wavelength in the required range the intra-cavity pulse can provide electrical fields at least five times higher than the one required with 1 m long modulator. These considerations suggest, that with such an architecture, the parameters of the electron beam, required to operate the oscillator could be significantly relaxed, which would contribute to easier and more reliable source operation.

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 - lower repetition rate beam. 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 where it is used for high charge beam energy modulation. While the modulator length can be chosen only once before the system is constructed, the transverse size of the mode can be made adjustable in a completed system. This can be accomplished either by deformable mirrors, or with the help of multiple 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.

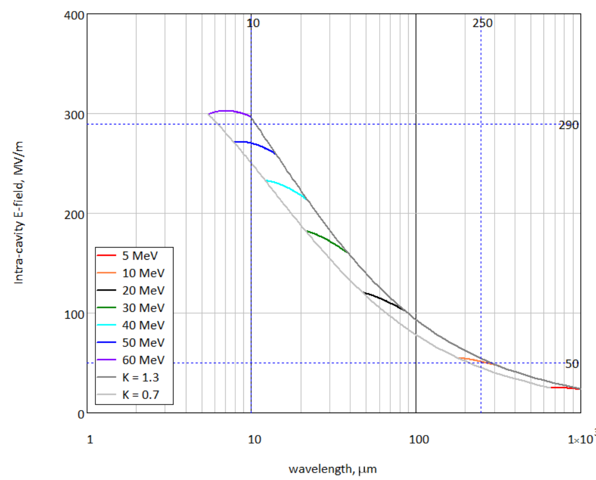

Figure 2: Amplitude of the FEL oscillator intra-cavity optical pulse.

SYSTEM LAYOUT OPTIOINS

Two possible layouts of the accelerator system are considered. Both schemes assume the use of two electron sources. First one provides an electron beam with high bunch charge of 1 nC and the repetition rate up to 1 MHz, for the radiation generation. Second one with bunch charge of up to 100 pC and repetition rate of 10 MHz, to drive the FEL oscillator. One possible layout uses single LINAC to accelerate two beams in opposite directions. 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. 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, accelerated in the opposite directions, would not meet in the LINAC. The main motivation behind this configuration is cost saving on the SRF LINAC and the LHe cryo plant. Another layout option assumes the use of two separate LINACs. The advantages of such layout are the simpler beam optics, and easier ways to organize multi-user operation, by providing independent beams to independent users from the two electron sources.

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