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NOVEL HIGH REPETITION RATE CW SRF LINAC-BASED MULTISPECTRAL PHOTON SOURCE

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Abstract

We discuss a design of a CW SRF linac-based photon facility for the generation of MIR-THz and VUV pulses at high repetition rates of up to 1 MHz. The MIR-THz sources would cover the frequency range from 0.1 to 30 THz with the pulse energies of a few 100 µJ. The use of the CW SRF linac and the radiation source architecture will allow for high flexibility in the pulse repetition rate. Conventional superradiant THz sources, driven by electron bunches shorter than the radiation wavelength, would cover the wavelength range from 0.1 THz to about 2.5 THz. A different approach is developed to extend the operation of the superradiant undulators well beyond the few THz. For this, a longitudinally modulated electron bunch would be used to achieve significant bunching factors at higher frequencies. The proposed VUV FEL would use the HGHG FEL scheme. It will allow the construction of a unique, fully coherent, high repetition rate source operated with about 30 µJ pulse energy at the first harmonic in the design wavelength range. An FEL oscillator, operating at a wavelength 3-5 times longer than the HGHG system, can generate the seed required for the high repetition rate HGHG scheme.

HIGH-FIELD MIR-THZ SOURCE

The Radiation Source ELBE at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) is a user facility based on a 1 mA - 40 MeV CW SRF LINAC. ELBE operates several high-repetition-rate IR and THz sources. Two FEL oscillators operating with a 13 MHz pulse repetition rate cover wavelength range from 5 through 250 µm and can deliver pulse energy of a few µJ. A superradiant undulator delivers 0.3 – 2.5 THz pulses at a few 100 kHz and pulse energy of a few µJ and operates simultaneously with a single-cycle coherent diffraction radiation source, which provides pulse energies of a few 100 nJ. There is a strong interest from the IR FEL and THz user community for pulse energies up to 1000 µJ! Another critical parameter of the required MIR-THz pulses is it's electrical field, which needs to reach a few MV/cm level. To achieve the required high pulse energies, a design of a new facility is under development.

One part of the new facility concept is a conventional superradiant undulator driven by a strongly compressed bunch. It is planned to operate the new facility with the bunch charge of 1 nC. It is also planned to use a second-order bunch compressor to remove the 2nd order RF curvature imprinted by the 1.3 GHz LINAC. In this case, micro-bunching instability estimations suggest that it will be possible to compress the bunch to about 200 fs (RMS). This will allow to increase the pulse energy to about 100 µJ, but only in the frequency range up to about 2 THz [1]. For the frequency range from 1.5 through 30 THz a different concept is being developed. Here instead of a strong bunch, compression longitudinal beam density modulation will be used. The scheme is inspired (naturally) by the FEL interaction process. The proposed scheme will operate similarly to HGHG FEL radiating at the first harmonic or an optical klystron. First, the beam energy will be modulated by a photon beam copropagating with the electron beam in an undulator-modulator. The energy modulation will be converted to a density modulation in a dispersive section. The modulation will be done at the wavelength of the desired radiation. We plan to operate such a source in the wavelength range from 10 µm through 250 µm. HGHG FEL theory shows that to maximize the beam bunching factor, the amplitude of the energy modulation needs to be comparable with the slice energy spread. Linear, 1D micro-bunching instability theory predicts allows estimating the growth of the slice energy spread to ~ 50 keV for the 1 nC bunch when it is accelerated to 50 MeV. For the concept robustness we assume that the energy modulation amplitude up to 200 keV might be necessary. An assumption of 1 m long modulator-undulator leads to the required amplitude of the modulating optical (MIR-THz) pulses of 40 MV/m with the pulse length of a few ps.

We argue that such modulating photon pulses in the wavelength range from 10 µm through 250 µm, with the requirements of (a) complete wavelength tunability and (b) repetition rate of up to 1 MHz, can be generated only by an FEL. Moreover, we intend to use the intracavity optical pulse of an FEL oscillator to relax the electron beam requirements. FEL modelling based on the set of J. Dattoli's analytical formulas [2], aided by empirical correction factors introduced by S. Benson, shows 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. For such modelling we assume (a) the use of an undulator with period of 100 mm and 40 periods, (b) electron beam parameters as presently used at ELBE: bunch charge of 77 pC, the RMS pulse length of 0.5 ps, the longitudinal emittance of 50 keV-ps, and transverse normalized emittance in both planes of 10 mm-mrad, and (c) an optical resonator with Rayleigh length of 1 m. We are considering implementing such an optical resonator as a ring resonator. Two undulators would be installed on the ring-resonator; one for the FEL generation and another for the high bunch charge beam energy modulation. A somewhat more detailed description of the proposed system layout can be found in [3].

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CW VUV FEL SYSTEM

On the landscape of synchrotron sources, the wavelength range from about 50 nm through 250 nm is not covered by any fully coherent (longitudinally and transversally), short-pulse (~ 100 fs), high-repetition-rate (MHz - class) facility. This is the gap in the wavelength range between the FLASH FEL facility operating at wavelengths shorter than 50 nm and the fourth harmonic of IR table-top laser systems. Such a source is proposed to be one of the key components of the new HZDR user facility.

LINAC and Electron Beam Parameters

Parameters of the electron beam play a crucial role in the performance of free-electron lasers (FEL). Here single bunch parameters and average beam current must be considered. The new photon source is envisioned as a user facility where very high reliability will be required. Hence, proven accelerator and beam technologies are preferable. We assume the use of ELBE accelerating modules [4]. The modules are made of two 9-cell TESLA-type SRF cavities and were initially designed at HZDR in collaboration with Stanford University. Several such modules have been in routine operation at the Radiation Source ELBE since 2001 and demonstrated reliable operation with an average current of up to 1.6 mA [5]. We are assuming the operation of the SRF LINAC with an accelerating gradient of 12.5 MV/m.

An efficient FEL operation requires a transverse (geometric) emittance smaller than $\lambda/4\pi$. With the shortest planned wavelength of 50 nm and 300 MeV necessary beam energy, we obtain the requirement on the transverse normalized emittance $\gamma\lambda/4\pi$ to be smaller than 2.3 mm-mrad. Considering that some transverse emittance degradation during beam transport and bunch compression is inevitable, we plan for the transverse emittance at the injector exit of about 1 mm-mrad. The required transverse emittance was demonstrated by APEX - the normal conducting, VHF, CW electron gun developed at LBNL - which will be used for the LCLS-II facility. The very high voltage (400 kV) DC photo-electron gun developed at Cornell University has demonstrated transverse emittance smaller than 0.5 μm at a bunch charge of 77 pC. Calculations show that such a combination of transverse emittance and bunch charge should be obtainable with the 3.5-cell 1.3 GHz SRF gun, which has been developed at HZDR [6].

Peak current is another critical parameter. For estimating the VUV FEL performance, an RMS bunch length of 200 fs is assumed. Experience with existing or previously operational accelerating system [7], supported by beam dynamics considerations, shows that such bunch length will be reliably achievable for 100 pC bunch charge at the beam energy of 300 MeV. It is envisioned that second-order linearization of the longitudinal phase space will be used.

One of the most critical, for an FEL, beam parameters is the uncorrelated energy spread. Micro-bunching instability estimations show that we shall expect the slice energy spread to grow to about 100 - 200 keV when the electron beam is accelerated to 300 MeV.

Estimated FEL Parameters

Reliable estimation of realistic FEL parameters can be made with the help of universal Ming Xie scaling [8]. Here we use the set of parameters described in the previous section to estimate the performance of the possible VUV FEL based on the existing SRF LINAC technology used at the Radiation Source ELBE. The central role in the Ming Xie scaling is played by the dimensionless parameter:

$$\rho = \left[\frac{1}{4\pi}\cdot\frac{{K_u}^2}{\left(1+{K_u}^2\right)^2}\cdot\frac{\gamma\,\lambda^2\,n_e\,{e_0}^2}{m_e c^2\,(4\pi\varepsilon_0)}\right]^{1/3}, \qquad (1)$$

where K_u is the RMS undulator parameter, γ is the relativistic Lorentz factor, n_e is electron beam density, e_0 is the electron charge, $m_e c^2$ is the rest mass of the electron, and λ is the radiation wavelength. For the wavelength range of interest and assuming the electron beam parameters set as described above ρ is about 2.5e-3. It was shown [9] that the saturation level of the FEL pulse intensity is described in terms of ρ as $P_{sat} = 1.6\,\rho\,(1+\eta)^{-2}\,P_{beam}$, where P_{beam} is the peak beam power, and η is the universal scaling function describing the reduction of the FEL efficiency due to the finite electron beam quality. Assuming that wavelength tuning is performed by changing the beam energy while keeping the undulator parameter $K_{rms} \approx 1$, where maximum FEL gain is achieved, we estimate the pulse energies on the order of 30 μJ for the entire wavelength range of interest. The universal scaling also allows estimating the undulator length necessary to achieve the saturation intensity. This is described in terms of the gain length parameter $L_g = \lambda_u/4\pi\sqrt{3}\rho$, where λ_u is the undulator period. Numerical modeling, in agreement with experiments, has shown that about 20 gain lengths are necessary to achieve the saturation intensity when FEL starts from noise. When the FEL process begins with a non-negligible bunching factor present in the electron beam, the required undulator length becomes shorter depending on the combination of the electron beam parameters. Assuming an undulator period of 25 mm, and the set of electron beam parameters described above, we estimate the undulator length for the saturation to be about 9 m.

A byproduct of an FEL operation is the generation of coherent harmonics. Both even and odd harmonics were experimentally observed. [10]. The power of the 2nd and 3rd harmonics were experimentally shown to be at the level of 1 % of the power at the fundamental wavelength. Thus, when an FEL operates near saturation with pulse energy at the level of 30 μJ, it automatically generates radiation with 2- and 3-times shorter wavelength than the fundamental one with the pulse energy at the level of 300 nJ. For the system described here, this means that radiation with wavelength down to 16.7 nm (75 eV photon energy) would be generated at such pulse energy levels at a repetition rate up to 5 MHz. This presents a significant interest for the potential user community of the CW VUV FEL.

FEL Scheme

Two key ideas of the source under consideration are (a) to provide fully coherent, transform-limited pulses with

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statistical and spectral properties better than the SASE process allows and (b) that availability of the high-repetition-rate CW electron beam allows the construction of an FEL, which does not rely on a single pulse process. Thus, the present baseline of the VUV FEL design is a high gain harmonic generation (HGHG) amplifier [11], with a seeding FEL oscillator driven by the CW electron beam.

For an HGHG amplifier, a sub-harmonic optical seeding pulse is necessary. For low repetition rate, normal conducting LINAC-based systems table-top laser systems are used for seeding [12]. For an MHz-class repetition rate system, most likely, a different solution will be needed. We plan to study the capabilities and limitations of a possible table-top laser-based seeding scheme when developing the technical design. However, at this point, we consider an FEL oscillator operating at the wavelength 3 - 5 times longer than the HGHG amplifier to be the first design option.

As mentioned earlier, we expect the uncorrelated energy spread to grow to about 100 - 200 keV due to the microbunching instability. For optimal HGHG performance, the energy modulation amplitude needs to be comparable with the slice energy spread. For 200 keV energy modulation of 300 MeV electron beam within 1 m long modulator-undulator, a co-propagating optical beam with an optical peak intensity of about 250 MV/m is needed. Assuming the radius of the optical modulating mode of 0.3 mm, which is a few times larger than the radius of the electron beam for stability and reliability reasons, leads to a peak power of the optical mode of 20 MW, or the pulse energy of 16 μJ. Modeling of an FEL oscillator shows that much higher optical peak power can be achieved by the FEL's intra-cavity pulse. We calculate the intracavity peak power, assuming the same set of electron beam parameters as for the HGHG amplifier, but used to generate radiation in the wavelength range from 150 nm through 450 nm. We also consider the use of broadband mirrors for the optical resonator to allow easier wavelength tunability and consider bare aluminum the primary mirror material candidate. Assuming 20 % total loss per round trip (10 % on each mirror), we calculate the intracavity peak power of 780 MW at 150 nm and 500 MW at 450 nm. Assuming 30 %, round trip loss results in 430 MW at 150 nm and 280 MW at 450 nm. Hence, an FEL oscillator operating at a pulse repetition rate of about 5 MHz is considered the primary seeding source candidate for the HGHG amplifier.

Driver Accelerator Configuration

The VUV FEL will need beam energy up to about 300 MeV. It is envisioned that a 5 MHz - 100 pC beam with an average current of 0.5 mA will be needed to drive the seeding oscillator. Another beam, interleaved with the first one, generated by the same electron source and accelerated in the same LINAC would be used for the HGHG amplifier. The pulse repetition rate of the second beam would be flexible with the upper limit of 5 MHz. The overall average current of the beam would be in the range between 0.5 mA and 1 mA. The SRF LINAC modules used at ELBE can accelerate higher average currents. The 1.6 mA operation was demonstrated already, and we estimate that a reliable 2 mA operation is possible. We can use this capability of the SRF LINAC to accelerate the CW electron beam with an average current of up to 2 mA to make the accelerator system more compact and less costly. We envision using 150 MeV LINAC in a recirculation set up similarly to the Continuous Electron Beam Accelerator Facility (CEBAF) [13]. In our case, a two-pass recirculation setup would be used. Estimates show that this would allow reducing the system cost by ~ 5 to 6 M€. The recirculation LINAC has several beam transport elements not present in a single-pass LINAC. Two *180° arcs* will be used to make the recirculation loop. The *merger* - the area where the beam with energy between 5 and 10 MeV from an injector and 150 MeV beam from the recirculation loop are put to one beam trajectory going into the LINAC for the first and second pass of acceleration, will be needed. At the exit of the LINAC, a *spreader* separates the two beams with energies of 150 MeV and 300 MeV without using any fast beam switching elements. One fast beam separation system will be needed to split the 10 MHz beam into the two beams – for the seeding oscillator and the HGHG amplifier. A prototype of the RF separator was designed and is being manufactured at HZDR within the program of the new facility development [14].

It is reasonable to expect that TESLA type SRF resonators, used within the ELBE modules, when prepared using modern methods of cleaning and treatment, can operate with the gradient of 12.5 MV/m (and even higher), essentially without field emission. The 150 MeV LINAC will need six ELBE-type accelerating modules with twelve accelerating cavities in total. The total length of such a LINAC would be about 22 m. Preliminary considerations suggest that the entire recirculation LINAC system, including an injector and the recirculation loop, would fit into a radiation enclosure with internal dimensions of about 41 m by 11 m. Figure 1 shows the layout of the proposed CW VUV FEL system schematically. The critical elements of the system are shown to scale.

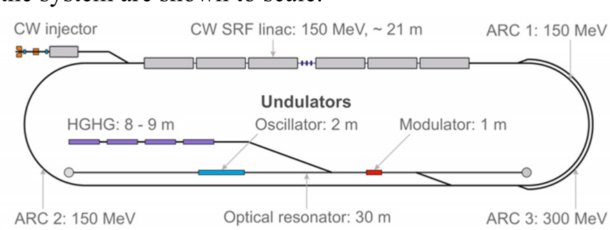

Figure 1: Schematic Layout of the VUV FEL system.

CONCLUSION

With the help of existing SRF LINAC (TESLA) technology used at HZDR by the Radiation Source ELBE in CW mode, a new, worldwide unique photon source-user facility could be constructed. Such a facility would allow combining in experiments high-field (>MV/cm) MIR-THz and fully coherent, transform-limited VUV pulses at a very high repetition rate. The two sources would operate simultaneously with < 100 fs synchronization level. HZDR will complete conceptual and technical design reports of the facility within the next few years.

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