TUNABLE IR/THZ SOURCE FOR PUMP PROBE EXPERIMENTS AT THE EUROPEAN XFEL

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Abstract

We present a concept of an accelerator based source of powerful, coherent IR/THz radiation for pump-probe experiments at the European XFEL. The electron accelerator is similar to that operating at the PITZ facility. It consists of an rf gun and a warm accelerating section (energy up to 30 MeV). The radiation is generated in an APPLE-II type undulator, thus providing polarization control. Radiation with wavelength below 200 micrometers is generated using the mechanism of SASE FEL. Powerful coherent radiation with wavelength above 200 micrometers is generated in the undulator by a tailored (compressed) electron beam. Properties of the radiation are: wavelength range is 10 to 1000 micrometers (30 THz - 0.3 THz), radiation pulse energy is up to a few hundred microjoule, peak power is 10 to 100 MW, spectrum bandwidth is 2 - 3 %. Pump-probe experiments involving ultrashort electron pulses can be realized as well. The time structure of the THz source and x-ray FEL are perfectly matched since the THz source is based on the same technology as the injector of the European XFEL. A similar scheme can also be realized at LCLS, SACLA, or SWISS FEL with S-band rf accelerator technology.

INTRODUCTION

Infrared and THz radiation is of high importance for applications in a wide variety of scientific fields like:

- study of quantum matter (strongly interacting quantum systems).
- magnetism and correlated states (High-Tc superconductivity, quantum Hall effect, Bose-Einstein condensation).
- complex fluids, petroleum, bio-fluids.
- study of structures and dynamics exploiting nuclear and electron magnetic resonance.
- condensed matter physics (nanoscale structure and determining phase diagrams).
- membrane proteins, bio-molecules (e.g. dynamics and function of metal ions in bio-systems).
- materials chemistry (element specific nuclear and electron spins, including quadrupolar nuclei).
- condensed matter technologies (glasses, ceramics, catalysts, zeolytes, batteries and fuel cells), etc.

Combination of IR/THz and x-ray pulses in pump-probe experiments at x-ray FEL facilities opens a new dimension to study the evolution of the above mentioned systems on atomic and molecular time scales [1–4].

An IR/THz source for pump-probe experiments at x-ray FELs should meet many requirements like tunability in a wide range (ideally from a fraction of micrometer up to a few millimeters), spectral and temporal properties, peak power, polarization, and the possibility for a precise synchronization with the x-ray pulse. For the moment, traditional techniques of IR/THz generation do not provide an universal solution for pump-probe experiments at x-ray FELs. Some part of the IR spectrum will be covered by quantum lasers. There are also developments of THz sources for pump-probe experiments. Each of such techniques may look to be a technically simple (table-top) solution, but an attempt to combine several devices in one place may lead to a complicated and expensive system.

Electron beams allow generating electromagnetic radiation in a wide wavelength range. Free electron lasers cover the full IR range [5–9]. Coherent radiation sources in a THz wavelength range operate in many location as well [10, 11]. Using the same electron beam to generate two colors for pump-probe experiments with a soft x-ray FEL has been implemented at FLASH [12–14]. The electron beam first generates the x-ray pulse in an x-ray undulator, and then passes a long period undulator and produces powerful, coherent undulator radiation at longer wavelengths down to the shortest scale of the electron bunch shape features. It has been shown experimentally that both pulses can be synchronized with femtosecond accuracy [15]. LCLS exploits the mechanism of coherent transition radiation (CTR) to generate THz radiation in a 2 μm thick Be foil placed after the x-ray undulator. A technical complication of such an approach is the necessity to transport the IR/THz radiation over long distances [13, 16, 17], but it is partially compensated by the good intrinsic synchronization of the IR/THz and x-ray pulses since they are generated by the same electron bunch. However, there exists a serious problem - nearly all application require the pump IR/THz pulse to come first. While there is no problem to delay the IR/THz radiation, it is an evident problem for x-rays. A solution of the problem can be to accelerate two closely spaced electron bunches such that the first bunch generates a IR/THz pulse with suppressed x-ray radiation [18, 19]. However, the first bunch always produces background radiation (spontaneous emission) which may be unacceptable for some experiments. To avoid this unwanted effect LCLS researches consider the option to bypass the x-ray undulator by the first bunch.

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Another option for a THz source is to generate IR/THz radiation by electron bunches from a separate electron accelerator [20]. In this report we present the concept of an accelerator based radiation source for pump probe experiments at the European XFEL. The accelerator consists of a laser driven rf gun and a warm accelerating section. The maximum electron energy is up to 30 MeV. With one APPLE-II - type undulator with a period of 4 cm it is possible to cover a wavelength range from 30 THz to 0.3 THz with narrow bandwidth. Radiation with wavelength below 200 micrometers is generated using the mechanism of SASE FEL. Radiation with wavelength above 200 micrometers is generated in the undulator by a tailored (compressed) electron beam. Installation of additional undulators with shorter (longer) period will allow further extension of the wavelength range. The proposed facility also assumes the installation of radiators for the production of a single-cycle radiation field using the mechanism of transition and edge radiation. Other types of diffraction radiators (e.g., Smith-Purcell, Cherenkov, etc) can be implemented as well.

The proposed facility is rather compact, and can be located in the experimental hall close to the experimental hutches. In this case the electron bunches can be transported to user's samples allowing to conduct pump-probe experiments with x-ray pulses, IR/THz pulses, ultra-short electron pulses (similar to Relativistic Electron Gun for Atomic Exploration (REGAE) facility at DESY [21]), and pulses from optical lasers.

ACCELERATOR BASED THZ SOURCE

The time structure and repetition rate of an IR/THz source for pump probe experiments must follow the time structure of the x-ray pulses. In the case of the European XFEL it is a burst mode of operation with 10 Hz macropulse repetition rate, and 2700 bunches within a macropulse separated by 222 ns. A radiation source based on an electron accelerator similar to the PITZ facility in Zeuthen ideally meets this requirement [22]. The current PITZ setup consists of a 1.6-cell L-band normal conducting copper gun cavity surrounded by main and bucking solenoids to focus the electron beams and counteract space charge forces. A Cs_2Te photocathode together with the photo cathode laser system is capable of producing long trains of electron bunches with individual charge up to several nC. Electron bunches with a maximum energy of 6.8 MeV generated in the gun are being further accelerated up to 25 MeV by a cut disk structure (CDS) booster cavity [23]. Currently the CDS booster is operated with RF pulses of up to 0.7 ms length at a repetition rate of 10 Hz [24]. Two 10 MW multi-beam klystrons are used to feed the rf gun and the CDS booster cavity. The photo cathode laser system is developed by the Max-Born-Institute (MBI, Berlin) and is capable of producing laser pulses with different temporal shapes, including Gaussian, flat-top without and with strong modulations [25]. A flat-top profile with up to 20-25 ps FWHM and ∼2 ps rise/fall time serves as a nominal temporal laser distribution. Transverse laser shaping is realized by imaging of a so-called beam shaping aperture (BSA) with variable diameter onto the photo cathode. A radial homogeneous distribution usually served as a goal for the transverse cathode laser profile tuning.

The high brightness PITZ photo injector was experimentally optimized for a wide range of bunch charges – from

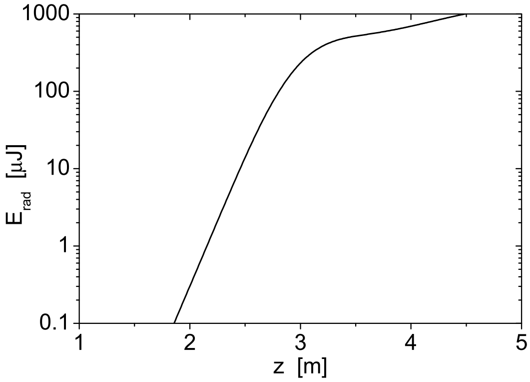

Figure 1: Energy in the radiation pulse versus undulator length for a SASE FEL operating at the wavelength of 100 μm. The bunch charge is equal to 4 nC, the peak current is 200 A. The simulations have been performed with the code FAST [26].

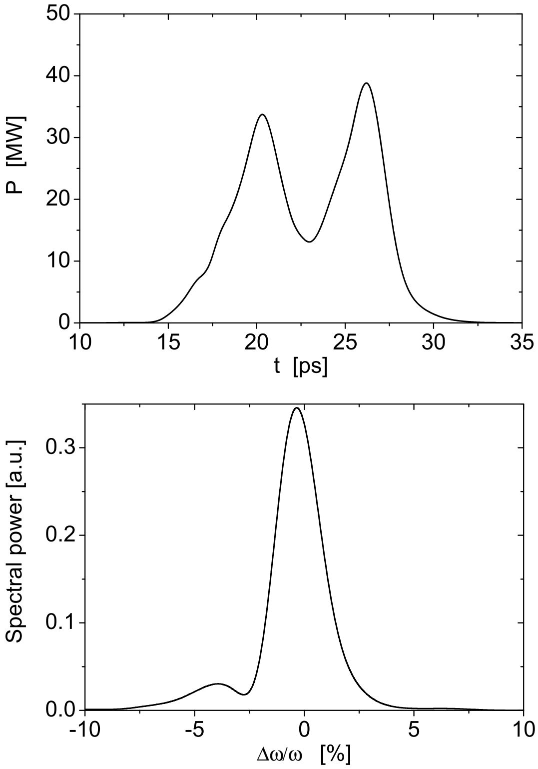

Figure 2: Temporal (top) and spectral (bottom) structure of the radiation pulse (single shot) from the SASE FEL operating at a wavelength of 100 μm. The bunch charge is equal to 4 nC, the peak current is 200 A. The simulations have been performed with the code FAST [26].

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20 pC to 2 nC [22], a possibility to produce bunch charges up to several nC was demonstrated.

In the following electron bunch parameters similar to those the PITZ facility can generate are assumed. The maximum electron energy is up to 30 MeV. The bunch charge can be tuned from a fraction of nC to 4 nC. The pulse duration can be varied in a wide range by means of tuning the drive laser pulse duration and application of a bunch compressor. It is assumed to install several radiators providing different properties of the radiation: undulators, diffraction radiators, radiators of coherent transition radiation (CTR) and edge radiators. Within the proposed source concept we can cover the electromagnetic spectrum from micrometer to millimeter wavelengths.

We proceed with demonstrating the undulator based radiation source. As an example we consider an APPLE-II - type undulator with a 4 cm period (see, e.g. [27]). Radiation in the wavelength range below 200 micrometers is generated in a SASE FEL starting from shot noise in the electron beam. Figure 1 shows the evolution of the average energy in the radiation pulse. In the saturation regime the SASE FEL can produce pulse energies up to 1 millijoule. The shot-to-shot fluctuations of the radiation energy in the saturation regime is below 10 %. Figure 2 shows the typical temporal and spectral structure of the radiation pulse. The peak power is about 30 MW, and the spectrum bandwidth is below 3 %.

Generation of coherent radiation in the undulator exploits the same idea as implemented at FLASH [12]. The radiation from a single electron possesses well known properties. For short electron bunches (or for bunches with sharp modulations) the radiation power is enhanced for radiation wavelengths longer than the typical feature size of the longitudinal bunch shape. In the case under study this mechanism can be used for generating wavelengths above 200 micrometers. This will allow to generate radiation pulses with prescribed spectral bandwidth by means of changing the undulator length. We do not highlight here properties of edge and CTR radiators and refer the reader to Refs. [17, 20]. Results presented in these studies can be easily scaled to the case under study.

The question to which minimum level the accelerator based THz source can be synchronized with the x-ray pulse is still open. One can rely on developments of precise rf synchronization systems for future x-ray FELs aiming at a goal to synchronize different subsystems located in different parts of the facility on a femtosecond level [28]. The present accuracy of synchronization of optical lasers and x-ray pulses is on a hundred femtosecond time scale. Since both accelerators use the same rf synchronization signal, one can hope that THz and x-ray pulses can be synchronized with the same accuracy.

THZ SOURCE IN THE TUNNEL

As it has been mentioned above, a jitter-free radiation source for pump-probe experiments is that when both colors are produced by the same electron bunch. Generation of the second color has been realized at FLASH with an FIR undulator having an undulator period 40 cm and a peak magnetic field of 1.1 T. Scaling of this device to the parameter range of the European XFEL requires high field devices (see Fig. 3). The present technological level of superconducting devices allows to reach peak fields of about 10 T [29]. The latter value together with a maximum electron energy of 17.5 GeV and maximum radiation wavelength of about 200 μm leads to the period length of about 100 cm. Similar devices of a down scaled length by a factor of 3 to 5 are in operation at storage rings. In principle, one module like that described in Ref. [29] can accommodate two or three undulator periods, and a string of several modules can form an undulator. Cooling is performed by a closed type He refrigerator providing low power consumption. It is practical experiences that such devices can operate for several months without He refilling [30].

Figure 4 traces the radiation pulse energy versus the radiation wavelength and the bunch charge for an undulator period of 100 cm and the number of periods equal to 10. The spectrum bandwidth is 10 %, correspondingly. The radiation pulse energies are rather high in the whole parameter space of bunch charges. Thus, installation of a

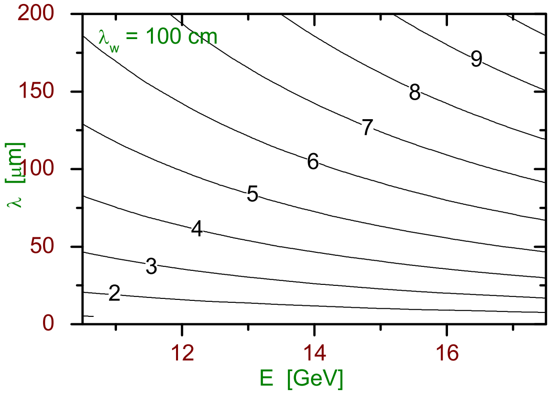

Figure 3: Peak magnetic field of the undulator for tuning to different wavelengths at different energies. The numbers denote the peak field in the units of T. The undulator period is equal to 100 cm.

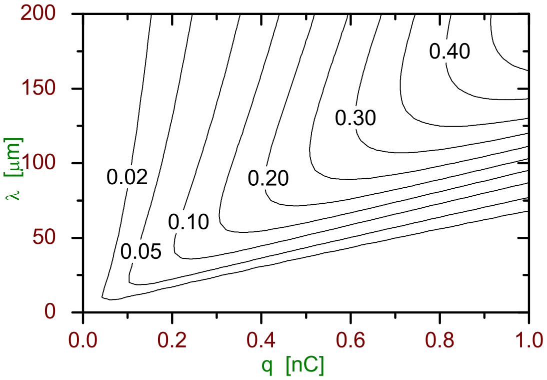

Figure 4: Pulse energy of the radiation from a FIR undulator at the European XFEL for tuning to different wavelengths at different bunch charges. The numbers denote the radiation pulse energy in units of mJ. The undulator period is equal to 100 cm.

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THz undulator can be an universal solution for a relatively narrow-band and rather powerful THz radiation source precisely synchronized with the FEL source. The technical solution does not seem to be bulky within the infrastructure of the whole project. However, one should remember that the radiation should be transported to the sample. There are pretty long distances at the European XFEL between the undulators and the experimental hall. A traditional photon beam line is not just a pipe, but a sequence of focusing mirrors. Its transverse size grows with the wavelength, and becomes unacceptably large for sub-millimeter wavelengths. An idea of using a diaphragm focusing line for transporting the radiation [31, 32] has been recalled recently [33]. This technique is not a universal one as well, and has limited frequency transmission band. For the moment we can state that despite there are several means to generate the second color well synchronized with the x-ray pulse, the problem of transporting the second color to the sample remains to be open.

DISCUSSION

Our estimations show that prices of both options to generate IR/THz radiation are comparable in view of the long transport lines required for an option accommodating the radiator in the tunnel. On the other hand, the option of a THz facility driven by an external accelerator has evident advantages in terms of a wider choice of radiators with different properties of the radiation and its quality in general. The electromagnetic spectrum of the radiation source covers the complete range of interest for user applications. In addition, a novel class of pump-probe experiments can be realized involving ultra short electron pulses. The scale of the facility is the same as of the PITZ facility at DESY in Zeuthen, and it can be easily fitted into the infrastructure of the European XFEL. The radiation from this single IR/THz source can be distributed among all the user stations like it is realized with optical lasers for pump probe experiments.

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