A SWEDISH COMPACT LINAC-BASED THz/X-RAY SOURCE AT FREIA

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Abstract

THz radiation enables probing and controlling low-energy excitations in matter such as molecular rotations, DNA dynamics, spin waves and Cooper pairs. In view of growing interest to the THz radiation, the Swedish FEL Center and FREIA Laboratory are working on the conceptual design of a compact multicolor photon source for multidisciplinary research. We present the preliminary design of such a source driven by high-brightness electron bunches produced by a superconducting linear accelerator. A THz source is envisioned as an FEL oscillator since this enables not only generation of THz pulses with a bandwidth down to 0.01% (with inter-pulse locking technique) but also generation of short pulses with several cycles in duration by detuning the resonator. For pump-probe experiments, the THz source will be complemented with an X-ray source. One of the most promising options is the inverse Compton scattering of quantum laser pulses from electron bunches. Such an X-ray source will operate from 1 to 4 keV with output intensity comparable to a second generation synchrotron. The envisioned THz/X-ray source is compact with a cost comparable to the cost of one beamline at a synchrotron.

INTRODUCTION

The energy of photons from the THz spectrum range corresponds to the energy of many types of excitations in matter such as low-frequency vibrations in large molecules, molecular rotations, lattice vibrations, spin waves, internal excitations of bound electron-hole pairs. A recent workshop *"The Science and Technology of Accelerator-Based THz Light Sources," Uppsala, November 18-19, 2013* clearly demonstrated a tremendous increase in applications of THz radiation in physics, material science and biomedicine. The analysis of literature and the presentations given at the workshop show that apart from a well-established time-domain THz spectroscopy [1], THz radiation allows coherent control of quantum transport in semiconductor superlattices [2], spin waves in antiferromagnets [3], quantum bits in semiconductors [4], high-Tc superconductivity [5]. The control was demonstrated experimentally.

THz radiation also finds a lot of applications in biophysics. In particular, it was reported that irradiation of mammalian stem cells with a THz field results in heterogenic changes in gene expression [6]. The proposed resonant mechanism of interaction of THz fields with stem cells predicts a creation of new open states in the double helix of DNA [7]. One more exciting application of THz radiation is connected to the study of chiral molecules, which are widely found in biology, for example, amino acids. Chirality plays an important role in medicine since drugs containing different enantiomers have different biological activity [8] because receptors, enzymes, antibodies and other elements of the human organism also exhibit chirality. Fingerprints of biological molecules belong to the THz region and it is foreseen that circularly polarized THz radiation can be used for studying chirality of bio-molecules.

In view of growing interest to the THz radiation, the Swedish FEL Center together with the FREIA Laboratory is studying the national user interest in THz physics and working on the conceptual design of a versatile photon source. The ultimate goal is to build a versatile THz/X-ray source for a multidisciplinary national user facility at the FREIA laboratory of Uppsala University. The photon source will be driven by high-brightness electron bunches produced by a superconducting linear accelerator (SC linac). In particular, we aim to combine an envisioned THz FEL with a soft X-ray source and such a combination will provide an opportunity for the time-resolved pump(THz)−probe(X-ray) measurements. Implementation of superconducting technology would greatly enhance flexibility of the envisioned multi-color photon source. Specifically, a photon source based on a SC linac enables the best flexibility in terms of bandwidth and wavelength tunability as well as scalability both in repetition rate and pulse energy [9]. Superconducting linacs enable operation in continuous wave (CW) or quasi-CW mode, which implies higher average brightness of the source. With a high duty factor operation, a SC linac also reduces the overall size of the facility and is economically more efficient than its normal conducting counterpart.

THE COMBINED THZ/X-RAY SOURCE

The conceptual layout of the combined THz/X-ray source is schematically shown in Fig. 1. A SC linac is followed by an X-ray source and a THz FEL oscillator.

One of the main challenges of the project is an electron source since high-brightness low-emittance electron bunches are needed for an efficient inverse Compton scattering process. Currently, only a SC photocathode RF gun can deliver bunches with the required parameters. However, this gun is complicated for fabrication and operation as well as expensive for a university facility. The search for an alternative lead us to a gun design, which is similar to the design proposed at Argonne [10]. The proposed gun utilizes a normal conducting (NC) 176 MHz re-entrant resonant cavity with an acceleration gradient of 20 MV/m. Note that an RF gun cavity of such geometry has been developed at the Lawrence Berkeley National Laboratory (USA) [11, 12] for the NGLS project. This cavity has a high thermal handling capabil-

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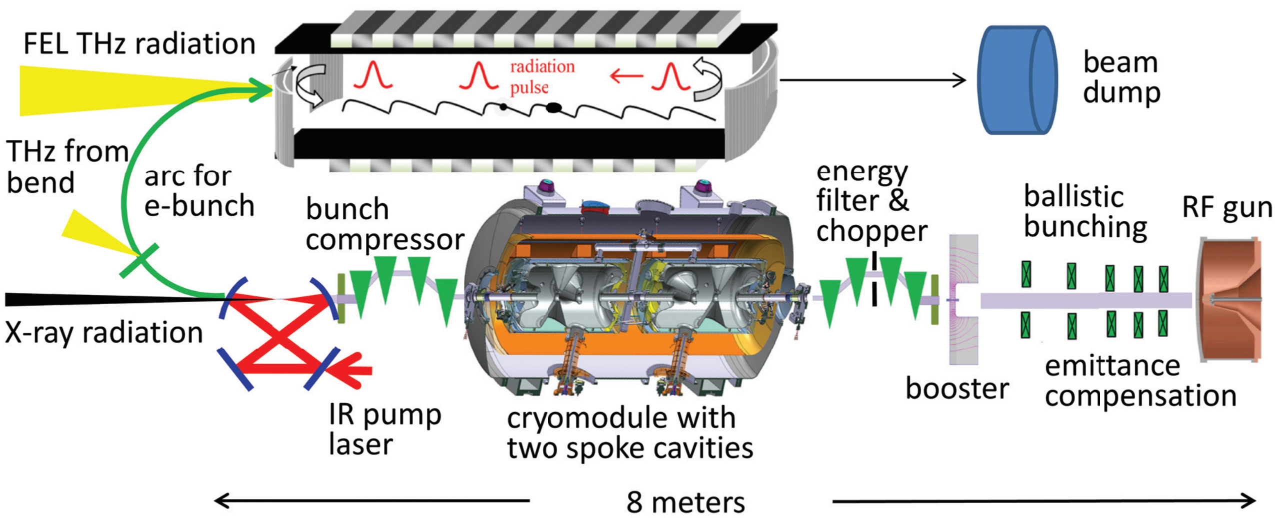

Figure 1: Schematic of a THz FEL complemented with an X- ray source.

ity and is suitable for CW operation. In order to achieve a low-emittance of 1 mm·mrad, the grid in our design is eliminated and electrons are injected into the gun cavity through a small aperture in the cavity wall. The thermionic cathode is located in the inner conductor of a stripline attached to the cavity walls. The cathode is isolated from RF fields of the gun cavity and 1 ns electron bunches are generated by applying RF pulses to the cathode via a stripline. Dark currents are suppressed by biasing. The gun is compatible with magnetic fields for emittance compensation and thermionic cathodes are capable of long-term, stable operation as this was demonstrated at Spring-8 (Japan) [13]. Simulations performed with the EGUN and PARMELA codes show that electron bunches with a charge of 0.7 nC, a duration of 1 ns, an energy of 0.4 MeV and an emittance of 1 mm·mrad can be generated. The shapes of the cathode and input/output apertures of the gun cavity were optimized in order to reduce the effects of electron beam aberration.

The NC thermionic gun has the advantages of long cathode life time (more than 20 000 hours in electron microscopes), the ease of operation and a robust and cost-efficient design. The disadvantage of such a gun is rather long electron bunches, which require an additional compression just after the RF gun. The longitudinal phase-space linearization will be done by means of the third harmonic of the gun cavity frequency. By using the third harmonic we also plan to create a non-linear energy chirp in order to compensate the non-linear dependence of the electrons transit time on their position in a bunch and obtain strong ballistic bunching [14].

The simulations performed with the simulation codes PARMELA and ASTRA show that 0.4 MeV, 0.7 nC bunches can be successfully compressed down to 10 ps within 2 meters by ballistic bunching. The use of the emittance compensation method with a solenoid allows us to keep the bunch emittance below 2 mm·mrad. A NC booster increases the bunch energy to 1 MeV for subsequent energy filtering. The energy filter (the first, from right to left, chicane shown in Fig. 1) reduces the energy spread to around 20 keV and the bunch charge to 0.2 nC, which is sufficient for the photon source. The average power deposited in the energy filter is below 100 W.

After the energy filter, electrons will be accelerated by two double-spoke cavities operating at 352.21 MHz. A recent study on high-beta spoke cavities for electron linacs [15] strongly indicates that the energy gain in a double-spoke cavity can be as much as 10 MeV. In this case the surface electric and magnetic fields are around 30 MV/m and 55 mT, respectively, which make the cavity operation stable. The spoke cavities will be powered by two RF sources able to deliver 400 kW peak power at 352.21 MHz with a duty cycle of 10%. The sources are being built at the FREIA laboratory within the FREIA-ESS project and are potentially available for use after 2018. A turn-key cryomodule hosting two double-spoke cavities is being developed within the ESS project as well and it will be available from industry. Only minor adaptations will be required. However, the spoke cavities have to be slightly re-designed for a high phase velocity.

Downstream the cryomodule, electron bunches are compressed in a magnetic chicane down to a few ps and collided head-to-head with an IR pulse produced by an external laser in order to produce X-rays via the inverse Compton scattering. The latter technique was experimentally proven in many laboratories [16]. Scattering of laser pulses with a wavelength of 1 μm on electrons with energies from 8 to 15 MeV will result in X-ray radiation from 1 keV to 4.3 keV.

A successful implementation of inverse Compton scattering requires very intense IR pulses with a repetition rate of 176 MHz, see the electron beam temporal structure in Fig. 2. A potential solution to this problem is the use of a so-called optical enhancement cavitiy [17]. The experimental studies [18] already demonstrated stable cavity operation with

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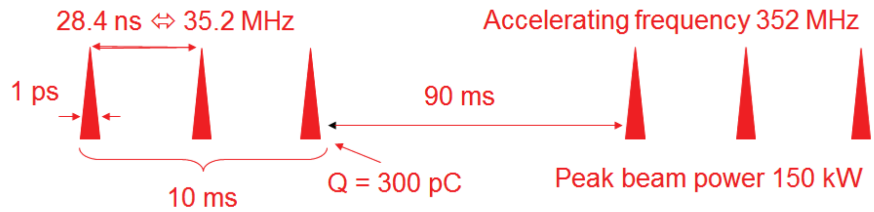

Figure 2: The proposed time structure of an electron beam at the end of the linac.

a power enhancement of around 1300 for average power of 670 kW at 1 μm wavelength and 250 MHz repetition rate. One should stress that the coherent enhancement of laser pulses in a passive cavity also provides ideal conditions for high-order HHG with multi-MHz repetition rate as it was recently demonstrated experimentally [19]. In our design, 1 mJ optical pulses will make a round trip with the repetition rate of electron bunches being equal to 176 MHz. This translates into 176 kW of average power circulating in the enhancement optical cavity during a 10 ms pulse. Note that a few ps laser pulses with a wavelength of 1 μm can be generated with up- to-date semiconductor lasers at the required power level.

Using results from the ref. [20], the analysis of X-ray emission predicts a peak and an average brightness of 5.7×10^{17} and 10^{13} photons/(s×mm^2×mrad^2×0.1% bw) respectively. The optical and electron beams are assumed to be tightly focused to a spot of around 60 μm. The coupling of the electron beam into the interaction region and of the X-rays out of it is currently planned through a 1 mm aperture in the cavity focusing mirrors. Another option for coupling of the electron beam would be to move one of the focusing mirrors into the centre of the magnetic chicane. This needs further investigation.

After the generation of X-rays, the electron beam is sent to a THz FEL configured as an oscillator located on top of the linac in order to make the system more compact. The latter allows not only generation of THz pulses with a bandwidth of 10^{-4} (with inter-pulse locking technique [21]) but also generation of short pulses with several cycles in duration by detuning the resonator [22]. The frequency will be tunable from 0.3 THz (1 mm) to 6 THz (50 μm) with a pulse energy 1-20 μJ. The temporal structure of the train of radiation pulses will reproduce the temporal structure of the electron beam presented in Fig. 2. For applications demanding a low repetition rate, a part of THz pulses will be re-directed to a different user station by inserting a mirror with changeable reflectivity in the THz transport line. Let us stress that in this case the THz FEL will serve two user stations.

By running the linac in a low-charge mode, one can generate short electron bunches, thus providing the possibility of generation of broadband THz pulses in the last dipole of the second chicane and/or in a dipole installed in the bending arc. The synchronization of THz and X-ray pulses for pump-probe experiments should be on a sub-ps scale and is quite challenging but feasible. For example, the synchronization at FLASH (DESY, Germany) is on a 10 fs level [23].

SUMMARY

We present the design of a compact combined THz/X-ray source driven by a SC linac. A combination of THz and X-ray radiation shall make possible pump-probe experiments on probing and controlling low-energy excitations in matter such as molecular rotations, DNA dynamics, spin waves and Cooper pairs. In addition, the proposed Compton X-ray source can be used as a stand-alone source and provide local users of synchrotron radiation with a tunable source suitable for phase-contrast imaging and protein crystallography.

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