FREIA Report 2014/01
March 2014

UPPSALA UNIVERSITET

DEPARTMENT OF PHYSICS AND ASTRONOMY
UPPSALA UNIVERSITY

Towards a combined THz/X-ray source:

report IV of the series of reports by the Swedish FEL Center and the FREIA Group

A. Opanasenko[a], V. Zhaunerchyk[b,c], V.A. Goryashko[b]

[a] National Science Center KIPT, Kharkiv, Ukraine
[b] Department of Physics and Astronomy, Uppsala University, Sweden
[c] Department of Physics, University of Gothenburg, Sweden

Department of
Physics and Astronomy
Uppsala University
P.O. Box 516
SE – 751 20 Uppsala
Sweden

Papers in the FREIA Report Series are published on internet in PDF- formats.
Download from http://uu.diva-portal.org

Uppsala University
FREIA Group

March 5th, 2013

vitaliy.goryashko@physics.uu.se

TOWARDS A COMBINED THZ/X-RAY SOURCE

Vitaliy Goryashko[a], Anatoliy Opanasenko[b], Vitali Zhaunerchyk[a,c] ,

[a] *Department of Physics and Astronomy, Uppsala University, Sweden*

[b] *National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine*

[c] *current address: Department of Physics, University of Gothenburg, Sweden*

Abstract

In the framework of development of a Free Electron Laser (FEL) by the Swedish FEL Center and the FREIA laboratory, we discuss the design of a versatile combined THz/X-ray source driven by high-brightness electron bunches produced by a superconducting linear accelerator. The ultimate goal is to build a versatile photon source for multidisciplinary research at the FREIA laboratory of Uppsala University. A significant part of equipment is potentially available via the FREIA project at Uppsala University after 2018 such as the cryogenic system, the system of power generation and transportation, control and data acquisition systems. For pump-probe experiments, we discus a possibility to combine the THz source with an X-ray source based on the inverse Compton scattering of quantum laser pulses from electron bunches. The X-ray source will operate in the "water window" with an output intensity comparable to a second generation synchrotron. The envisioned THz/X-ray source is compact and comparable in budget to the cost of one beamline at MAX IV. The source can also be used to train students in accelerator physics and applications of THz and synchrotron radiation.

During the workshop on *"The Science and Technology of Accelerator-Based THz Light Sources", Uppsala, November 18-19, 2013* (supported by the Nobel Institute for Physics and the FEL Centre) we learned a valued lesson on a great importance of having a flexible source operating in different wavelength ranges and able to serve different users stations. In particular, the combination of THz and X-ray radiation is very interesting for pump-probe experiments. Recall that advanced X-ray FELs like LCLS (USA), FLASH and European XFEL (Germany), FERMI@Elettra (Italy) and SwissFEL (Switzerland) will be or already are complemented with THz light sources. In our case, it will certainly be beneficial to have an X-ray source in addition to the THz source. Possible methods to generate X-rays with electron bunches are bremsstrahlung, channeling and parametric radiation, inverse Compton scattering. The latter can compete with high-harmonic generation in terms of the quality of X-ray radiation.

Let us recall that among different compact schemes of generation of narrow-band extreme ultraviolet/X-ray, the high-harmonic generation (HHG) in gases and the inverse Compton scattering are probably the most proven schemes [3]. HHG in gases driven by femtosecond lasers offers a tabletop-scale, tunable extreme ultraviolet source with full spatial and temporal coherence and ultrashort pulse duration. The repetition rate of HHG sources is determined by rates of optical

lasers, which they are driven by, and can be as high as tens of kHz. However, to date only high harmonics at photon energies of around 0.5 keV has been demonstrated [4]. At the same time, inverse Compton scattering – based on the back-scattering of light from free electrons – allows generation of photons also with higher energies. The photon energy E_{ph} can be tuned over a broad range by changing the electron beam energy E_b since E_{ph} is proportional to E_b^2. Specifically, for a head-on collision $E_{ph} = 4\gamma^2 E_{ph}^{pump}$, where γ is the electron beam energy in units of the rest mass and E_{ph}^{pump} is the energy of photons of a pump laser. For high-brightness pulsed applications, a source at BNL laboratory demonstrated peak brightness in excess of 2.8×10^{18} photons/(s×mm^2×mrad^2×0.1% bw) at 0.18 nm. The MIT concept [6] based on high repetition rate SC linac would significantly improve the peak and average brightness, giving 10^{23} and 10^{15} photons/(s×mm^2×mrad^2×0.1% bw), respectively. The generated ps X-ray pulses can be, for example, used as a probe whereas THz pulses as a pump for low-energy excitations in matter such as molecular rotations, spin waves and Cooper pairs. etc. [7, 8, 9, 10].

The X-ray source using inverse Compton scattering can be build on the base of the RF linac discussed in [11] so that it seems beneficial to study this option. This work is underway and here we will briefly mention only the main idea illustrated by Fig. 1. The electron beam generated by the thermionic RF gun discussed in [11] will first be compressed by means of ballistic bunching, then accelerated to 1 MeV by a NC booster and filtered by an energy filter. After the filter, electrons are accelerated by two spoke cavities. Two RF sources for spoke cavities will be available at the FREIA laboratory so that the spoke cavities are considered as an alternative for an elliptical cavity. The energy gain of spokes is sufficient and they can operate at 4 K, which is economically more efficient than operation at 1.8 K.

Downstream the cryomodule, the electron beam is compressed in a magnetic chicane down to a few ps. Just after the compressor, the transversely focused electron bunches are collided head-to-head with IR pulses in an optical cavity pumped by an external laser. X-rays are generated via inverse Compton scattering. This technique was experimentally proven in many laboratories [3]. Scattering of 10 μm laser pulses on electrons with energy from 10 to 16 MeV will result in X-

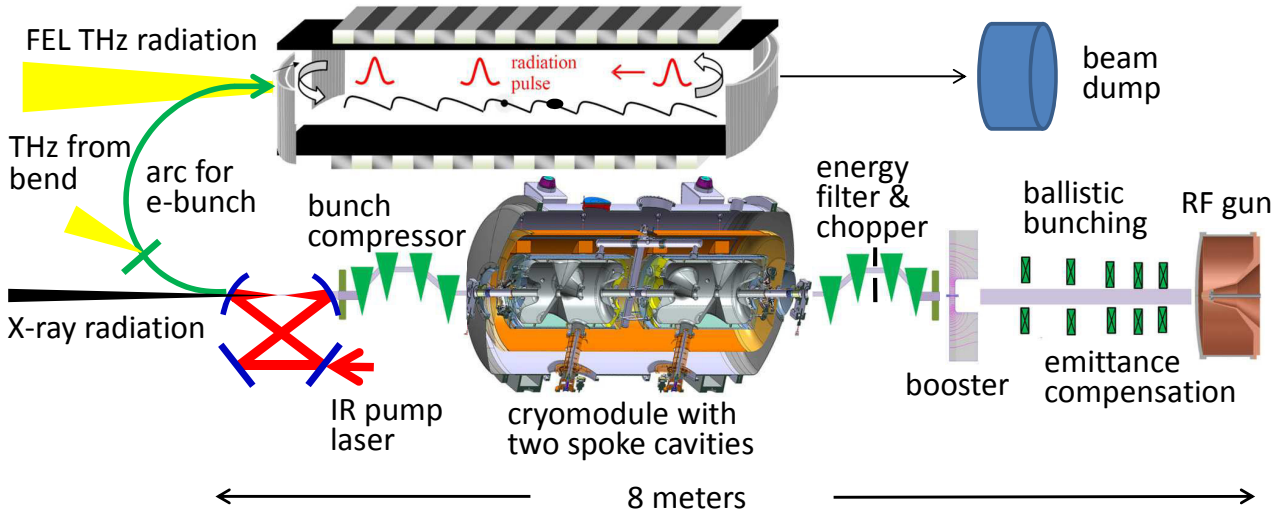

Figure 1: Schematic of a THz FEL complemented with an X- ray source.

ray radiation from 0.2 keV to 0.5 keV ("water window"). In order to obtain optical pulses of a high energy with a multi-MHz repetition rate, an enhancement optical cavity can be used. A train of a few ps optical pulses from a CO_2 laser will be coherently coupled into this cavity. Note that generation of ps pulses with a CO_2 laser is non-trivial because of the narrow-band line of amplification of this type of lasers. A possible solution to this problem was experimentally demonstrated at the Brookhaven laboratory [12], where a CO_2 laser was driven by an external solid-state laser. The natural bandwidth of the 350-fs injected pulses is about threefold broader than that of a CO_2 amplification band. Hence, the pulse spectrum will shrink upon amplification, with a simultaneous rise in its duration to 1.5-2 ps.

Experimental studies [13] already demonstrated a stable cavity operation with a power enhancement of around 1400 for an average power of 78 kW at 1 μm. Further studies [14] suggest the possibility of circulation of 1 MW average power in an enhancement optical cavity. 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. The average power required from a pump laser is around 130 W. We will carry out further work on the laser system and enhancement optical cavity. Using results from ref. [15], the analysis of X-ray emission predicts a peak and an average brightness of 5.7×10^{18} and 10^{14} photons/(s$\times$mm$^2\times$mrad$^2\times$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 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} but also generation of short pulses with several cycles in duration by detuning the resonator [16]. 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. An external laser will irradiate the mirror and create a dense electron plasma, making the mirror reflecting for several nanoseconds [17].

By running the linac in a special mode with low charge short electron bunches, one has a possibility to generate short THz pulses in a bending magnet installed in the bending arc. This

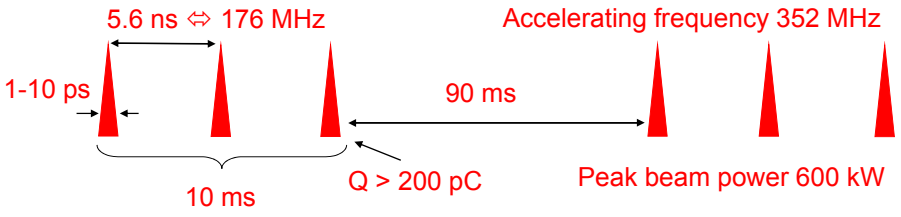

Figure 2: The proposed time structure of an electron beam at the end of the linac.

option needs to be studied in more detail. The proposed combined THz/X-ray source would allow several possible modes of operation with a repetition rate of 176 MHz

- THz FEL oscillator;
- X-ray source;
- hybrid mode I: X-ray source and FEL oscillator;
- hybrid mode II: X-ray source and short THz pulses produced via synchrotron radiation in a bending magnet;
- hybrid mode III: X-ray source and THz pulses from SASE FEL with a good balance of bandwidth and duration.

The proposed compact X-ray source can provide local users of synchrotron radiation with a tunable source suitable for phase-contrast imaging and protein crystallography. A combination of THz and X-ray makes possible pump-probe experiments. One can always run one or another source but the hybrid modes of operation need further studies. The synchronization has to be on a ps scale and this is a challenge.

References

[1] Workshop on the Science and Technology of Accelerator Based THz Light Sources. 18-19 Nov. 2013, Uppsala University, Sweden.

[2] private communication by Keith Nelson

[3] Workshop on Compact Light Sources 11-12 May 2010, Rockville, USA.

[4] M.-C. Chen et al., Proc. of CLEO-2010, JThI3, 16-21 May 2010, San Jose, USA.

[5] I.V. Pogorelsky et al., PRST-AB 3, 090702 (2000).

[6] W.S.Graves et al., Nucl. Instrum. Methods A 608, S103 (2009).

[7] B.J. Keay et al., Phys. Rev. Lett., 75, 4102x964105 (1995).

[8] T. Kampfrath et al., Nature Photonics 5, 31-34 (2011).

[9] B. E. Cole et al., Letters to Nature 410, 60-63 (2001).

[10] A. Dienst et al., Nature Materials 12, 535-541 (2013).

[11] A. Opanasenko, V. Zhaunerchyk, V. Goryashko, "Design of a Superconducting Linear RF Accelerator for a Superradiant THz FEL: report II of the series of reports by the Swedish FEL Center and the FREIA Group," FREIA Report 2013/05, (2013).

[12] ATF CO2 Laser Upgrade Plan: white paper
`http://www.c-ad.bnl.gov/ardd/Laser\%20Upgrade/whitepaper.pdf`

[13] I. Pupeza *et al.*, Optics Letters **35**, 2052 (2010).

[14] I. Pupeza, "Power Scaling of Enhancement Cavities for Nonlinear Optics," PhD thesis, München, September 8 (2011).

[15] F. V. Hartemann *et al.*, Phys. Rev. ST Accel. Beams **8**, 100702 (2005).

[16] G.M.H. Knippels et al., Phys. Rev. Lett. 75, 1755x961758 (1995).

[17] G.M.H Knippels, A.F.G van der Meer, Nucl. Instrum. Methods B 144, 32-39 (1998).