Development of a Facility for Probing the Structural Dynamics of Materials with Femtosecond X-ray Pulses

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Abstract

We propose to use Thomson backscattering of far-infrared (FIR) pulses (100-300 μm wavelength range) by a 500 MeV electron beam to generate femtosecond X-rays at the TESLA Test Facility (TTF) at DESY. Using the parameters of the photocathode rf gun and the magnetic bunch compressors of the TESLA Test Facility (TTF), it is shown that electron pulses of 100-fs (FWHM) duration can be generated. Passing the short electron bunches through an undulator (after the conversion point) can provide a FIR high-power source with laser-like characteristics. On the basis of the TTF parameters we expect to produce X-ray pulses with 100-fs duration, an average brilliance of nearly 10^{13} photons s^{-1} mrad^{-2} mm^{-2} per 0.1% BW at a photon energy 50 keV. The total number of Thomson backscattered photons, produced by a single passage of the electron bunch through the mirror focus, can exceed 10^7 photons/pulse. We also describe the basic ideas for an upgrade to shorter X-ray pulse duration. It is demonstrated that the TTF has the capability of reaching the 10^{12} photons s^{-1} mrad^{-2} mm^{-2} per 0.1% BW brilliance at a ten femtosecond scale pulse duration.

1. Introduction

Understanding the structural dynamics of materials on the fundamental time scale of atomic motion represents an important frontier in condensed matter research because chemical reactions, phase transitions, and surface processes are ultimately driven by the motion of atoms on the time scale of one vibrational period ($\simeq$ 100 fs). Resent efforts at applying X-rays to probe structural dynamics have used

Table 1
Major electron beam parameters for 100 fs-scale X-ray facility option

Parameter	Value
beam energy	500 MeV
transverse emittance	$2\ \pi$ mm-mrad/γ
longitudinal emittance	$30\ \pi$ keV-mm
bunch charge	1 nC
bunch repetition rate	9 MHz
duty factor	1%

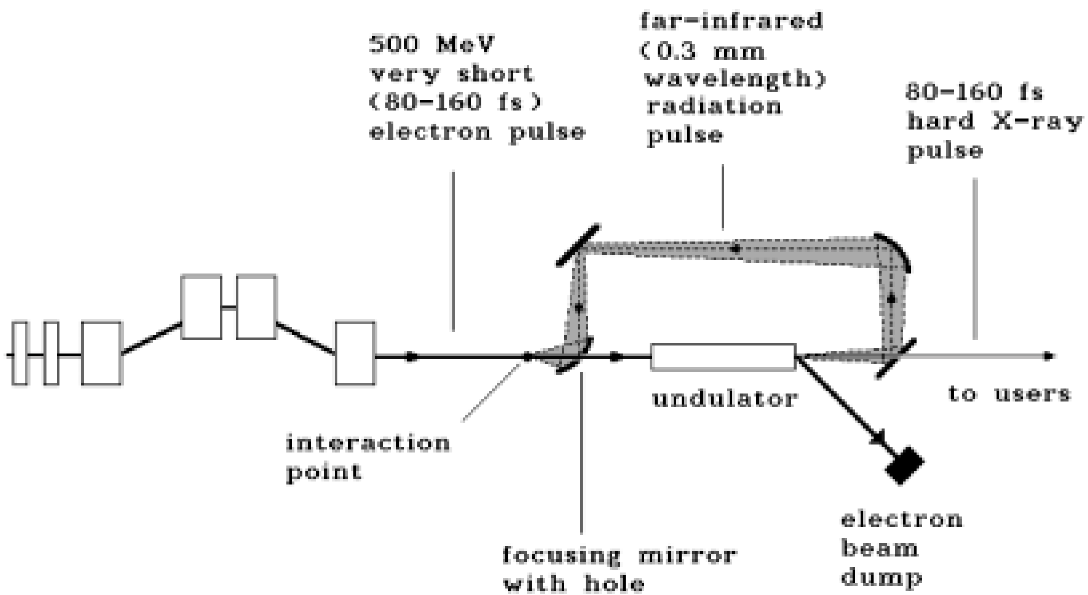

Fig. 1. Basic scheme of the femtosecond X-ray facility

a synchrotron source combined with a femtosecond optical laser [1]. Femtosecond synchrotron radiation pulses were generated directly from an electron storage ring ALS. An ultrashort laser pulse was used to modulate the energy of electrons within a 100-femtosecond slice of the stored 30-picosecond electron bunch. The energy-modulated electrons were spatially separated from the long bunch and used to generate 300-femtosecond X-ray pulses at a bending magnet beamline. The same technique can be used to generate 100-femtosecond X-ray pulses. On the basis of the parameters of an ALS small-gap undulator and for example, laser pulses of 25 fs and 100 μJ at a repetition of rate 20 kHz, Schoenlein and co-workers expect in the future an average brilliance of 10^{11} photons s^{-1} mrad^{-2} mm^{-2} per 0.1% BW at a photon energy of 2 keV.

Another project of a femtosecond X-ray facility, which is described in detail in this paper, is based on the idea to use Thomson backscattering of a high power far-infrared radiation pulse from a relativistic electron bunch. In our project we use 500 MeV electron bunches from the Tesla Test Facility (TTF) linear accelerator [2] and 200 MW optical pulses from a FIR source based on coherent undulator radiation (see Fig. 1). The basic TTF electron beam parameters are given in Table 1. In a backscattering geometry,

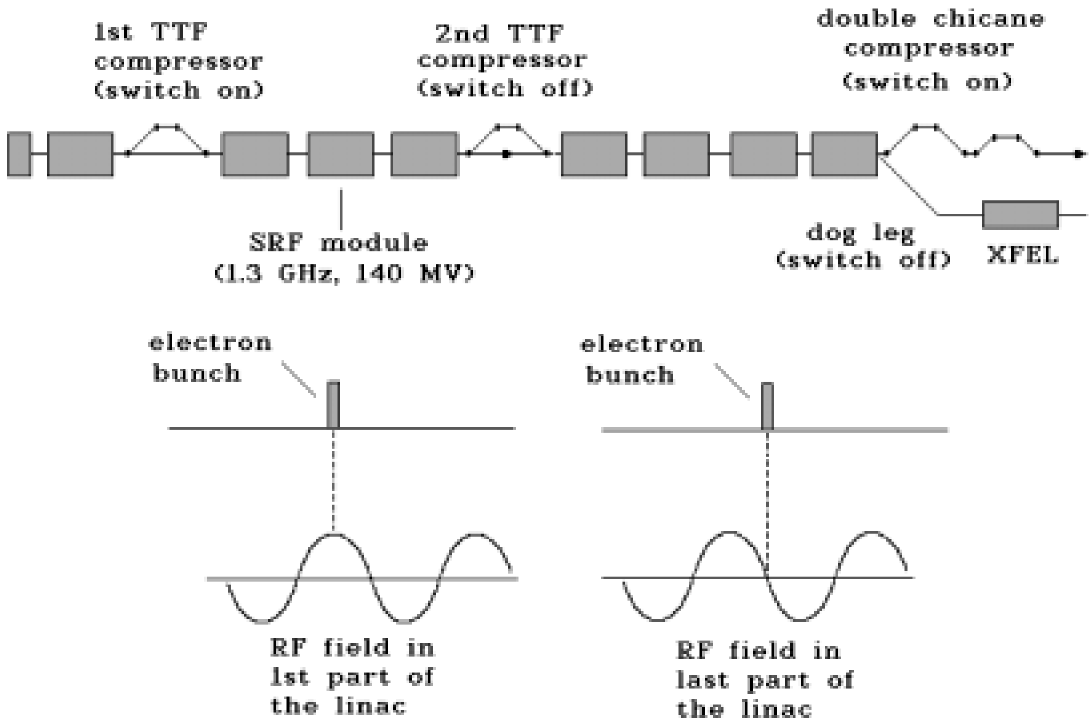

Fig. 2. Femtosecond X-ray facility compression and acceleration schematic

the duration of the scattered X-ray burst is determined by the length of the electron bunch. In order to achieve a small bunch length in the conversion point, the bunch must be compressed in magnetic chicanes. For this project we assume to use a two-stage compressor design (see Fig. 2). The first TTF magnetic chicane compresses the bunch from $\sigma_z \simeq 1.6$ mm to $\sigma_z \simeq 0.4$ mm. After the first bunch compressor the electron bunch is accelerated in the next part of the TTF linac from 150 MeV to 500 MeV energy. Then the electron bunch passes the last part of the accelerating structure (voltage $V = 500$ MV) at 90° crossing phase and the energy spread of the electron beam is increased to about 5 MeV. The electron bunch with such large correlated energy spread can be compressed in special double magnetic chicane down to $\sigma_z \simeq 10\ \mu$m.

2. Yield of X-ray photons

We propose to install a special undulator after the interaction point. Intense, coherent far-infrared undulator radiation can be produced from electron bunches at wavelengths longer than the bunch length. The undulator equation $\omega_0 = 2ck_\mathrm{w}\gamma^2\left[1 + K^2/2\right]^{-1}$ tells us the resonance frequency of radiation as a function of undulator period $\lambda_\mathrm{w} = 2\pi/k_\mathrm{w}$, undulator parameter K and relativistic factor γ. Note that for radiation within the central cone the relative spectral bandwidth $\Delta\omega/\omega \simeq 1/N_\mathrm{w}$, where N_w is the number of undulator periods. The energy radiated into the central cone in the case when the resonance wave length much longer that the bunch length is given by ($K^2 \gg 1$): $\Delta E_\mathrm{con} \simeq \pi e^2\omega_0 N_\mathrm{e}^2/c$.

The planar undulator is an inexpensive electromagnetic device with 20 periods, each 60 cm long. At the operation wavelength of the FIR source around 100 μm and an electron beam energy of 500 MeV the peak value of the magnetic field is about 0.5 T. In the case when the number of electron per bunch is about $N_e = 6 \times 10^9$ (1 nC) the FIR source described above provides a train of 6.6 ps long micropulses (the wave advances the electron beam by one wavelength at one undulator period), with 1.5 mJ of optical energy per micropulse radiated into the central cone at 100 μm wavelength. To provide a natural selection of coherent radiation in the central cone ($\theta_{\rm cone} \simeq 4$ mrad), the radius of the mirror should be equal to 5 cm at a distance of about 10 meters between the exit of the FIR undulator and the mirror.

To obtain an effective conversion of the primary photons into X-ray photons, the far-infrared beam should be focused on the electron beam. This may be performed, for instance, by means of a metal focusing mirror (see Fig. 1). Electrons move along the z axis and pass through the mirror focus. The conditions of optimal focusing are as follow ($l_e \ll l_{\rm opt}$):

$$\sigma_{x,y}^2 \ll [4cF/(\omega a_0)]^2 \ , \quad F^2 \ll a_0^2 l_{\rm opt}/(2\lambda) \ ,$$

where $\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}}$ is the transverse electron beam size at the conversion point, $\beta_{x,y}$ is the beta function, $\epsilon_{x,y}$ is transverse emittance of the electron beam, F is the focal length of the mirror, a_0 is the radius of the optical beam spot on the mirror, l_e and $l_{\rm opt}$ are the lengths of electron and optical bunch, respectively. The first condition assumes the transverse size of the electron beam at the conversion point to be much less than the FIR beam size. The second condition means that the characteristic axial size of the region with a strong optical field is much less than the length of the optical bunch.

Hard X-ray photons are produced by means of Thomson backscattering of the optical photons by the high energy electrons. Relativistic effects cause the X-ray flux to be strongly peaked in the forward direction; for the 500 MeV electron beam ($\gamma = 10^3$) and 100 μm radiation wavelength used in our project, the Thomson backscattered X-rays are peaked at a maximum energy $\hbar\omega_{\rm x-ray} = 4\gamma^2\hbar\omega_{\rm opt} \simeq 50$ keV.

When the conditions of optimal focusing are fulfilled the total number of X-ray photons, produced by a single passage of the electron beam through the mirror focus, is given by the following relation:

$$\Delta N_{\rm x-ray} = \frac{2W\sigma_{\rm T}}{\hbar c^2} N_e \ ,$$

where $\sigma_{\rm T}$ is the total Thomson cross section, N_e is the number of electrons in the bunch, and W is the peak power of the optical beam. An important feature of the obtained result is that the number of produced X-ray photons does not depend on the details of the optical field distribution at the mirror surface and is defined by the peak optical beam power only. Taking into account the TTF parameters and FIR source parameters (see Table 1) and assuming that the conditions of optimal focusing are fulfilled, we obtain a yield of X-ray photons of $\mathrm{d}\, N_{\rm x-ray}/\mathrm{d}\, t \simeq 2 \times 10^{12}\ \mathrm{s}^{-1}$.

The quality of the radiation source is described usually by the brilliance defined as the density of photons in the six-dimensional phase space volume:

$$B = \frac{1}{4\pi^2\sigma_x\sigma_x'\sigma_y\sigma_y'} \left(\lambda \frac{\mathrm{d}^2 N_{\rm ph}}{\mathrm{d}\,\lambda\,\mathrm{d}\,t}\right) \ .$$

Let us proceed with numerical example for 160 fs (FWHM) electron pulse duration. The main parameters of the electron beam are presented in Table 1. The source of primary photons has the following parameters: wavelength 100 μm, peak power $W \simeq 250$ MW, pulse duration 6.6 ps. Assuming the focus distance of the mirror to be equal to $F \simeq 20$ cm and the radius of the FIR beam at the focusing mirror $a_0 \simeq 10$ cm we find that the condition of optimal focusing will be fulfilled at $\beta \simeq 10$ cm. Under these conditions we calculate an average brilliance of 10^{13} photons s^{-1} mrad^{-2} mm^{-2} per 0.1% BW at a photon energy of 50 keV

In order to produce 80 fs long electron pulses the bunch charge must be reduced to about 0.3 nC. It will be done in stages to avoid coherent synchrotron radiation effects (longitudinal wakefield) limiting the achievable bunch length and beam emittance. On the basis of the parameters of the electron beam with 80-fs pulses and the FIR source we expect an average brilliance of about 10^{12} photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% BW at a photon energy of 50 keV.

3. Bunch compressors

The proposed phase bunching system is sketched in Fig. 2. Compressing the bunch will be done in stages to avoid space charge and coherent synchrotron radiation (CSR) effects limiting the achievable bunch length and transverse emittance. The first compression is from 1.6 mm to 400 μm. It consists of a 150 MeV accelerating module followed by the first TTF magnetic chicane generating the R_{56} needed for bunch compression [3]. Calculations show that induced energy spread and emittance dilution should not be a serious limitation in BC1 [3].

After leaving the first bunch compressor the electron bunch of 400μm length is accelerated in the next part of the TTF linac with an on-crest phase from 150 MeV to 500 MeV. For the second compression the required large correlated energy spread in the bunch of 5 MeV is induced by passing the last part of the accelerating structure at 90° crossing phase. Our analysis shows that adequate solution for the BC2 design is a double chicane. Each chicane is twelve meters long and contains four C-type rectangular bending magnets. For compression from 400 μm to 20 μm the parameters of BC2 are practically identical to that designed for LCLS BC2 [4]. The first and second chicanes generate $R_{56} = 3$ cm and 0.3 cm at bend angle $\theta_{\mathrm{B1}} = 3.4^{\circ}$ and $\theta_{\mathrm{B2}} = 1.3^{\circ}$, respectively. Four quadrupoles are placed between the chicanes in locations where the dispersion passes through zero. Since the energy spread generated by CSR is coherent along the bunch, its effect on the transverse emittance can be compensated in a double chicane with optical symmetry to cancel the longitudinal-to-transverse coupling [4].

4. Future potential

For the 100-femtosecond X-ray facility described above, we have adopted the TTF design parameters for the photocathode rf gun injector [2]. In order to achieve a 5 μm rms bunch length (40-fs pulse duration) a new mode of operation of the TTF injector is required. The injector should produce 100 pC bunches with a longitudinal emittance of 10 π keV-mm and a normalized transverse emittance of 1 π mm-mrad. In order to reach $B \simeq 10^{13}$ photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% BW, the bunch repetition rate (within a macropulse) would have to be increased up to 108 MHz. Such values of bunch charge and repetition rate would keep the mean value of average current during a macropulse and the mean power of the laser system (below 2 W) at the TTF design level. As a result, no modifications are necessary for the rf gun. In this high repetition rate option only the laser system needs hardware modifications.

Analysis of the TTF parameters shows that an extension to bunch lengths shorter than 5 μm rms is also direct and straightforward but needs increasing linear correlated energy spread. Compressing the bunch in our case will be done in stages to avoid RF curvature effect. The proposed solution is to perform compression in three steps: compression at 150 MeV, decompression at 500 MeV before the last part of the linac and compression at 500 MeV at the linac exit. In this scheme the energy spread of the electron beam is increased to about 15 MeV. An electron bunch with such a large correlated energy spread and 30 pC charge per bunch, can be compressed in a special double magnetic chicane down to $\sigma_z \simeq 2$ μm. The average brilliance of such a 10 fs-scale X-ray facility could reach a value of $B \simeq 10^{11}$ photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% BW. This requires installation of an additional chicane for decompression and modification of the photoinjector laser system.

The yield of X-ray photons may be increased further more by means of organizing several conversion points. After crossing the first conversion point, the optical beam is directed to an optical delay line and then it is focused at the next electron bunch, etc. Taking into account that the reflection losses of metal focusing mirrors for radiation of 100 μm wavelength are only about 0.5%, we may conclude that each optical bunch can effectively interact with many electron bunches. As a result, a yield of X-ray photons may be increased by a factor of about 10.

Acknowledgments

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