LINAC-Based Synchrotron Radiation Facility with Femtosecond Soft X-ray Pulses

W. Brefeld [a] W. B. Faatz [a], J. Feldhaus [a], K. Floettmann [a], M. Körfer [a], J. Krzywinski [b], T. Limberg [a], T. Möller [a], J. Pflueger [a], J. Rossbach [a], E.L. Saldin [a], E.A. Schneidmiller [a], S. Schreiber [a] and M.V. Yurkov [c]

[a] *Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany*

[b] *Institute of Physics of the Polish Academy of Sciences, 02688 Warszawa, Poland*

[c] *Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia*

Abstract

In this paper we perform design consideration of a femtosecond linac-based synchrotron radiation facility. Proposed technique is based on the generation of energy chirped short electron bunches that would subsequently spontaneously radiate frequency chirped soft X-ray pulses in an undulator. These pulses are then spectrally dispersed using grazing incident grating. The spectrum is propagated through exit slit (spectral window) which filters the pulses of femtosecond duration. The shortest temporal structures (about 10 fs) are limited by the energy chirp and longitudinal emittance of the electron bunch, number of undulator periods, and resolution of monochromator. In this paper we analyze potential of the TESLA Test Facility (TTF) at DESY for construction of such a femtosecond X-ray facility. TTF linac would be able to deliver up 500-700 MeV electron beam, prepared with properties to allow generation of fs soft X-ray pulse (with electron pulse duration 0.16 ps FWHM, energy chirp 1 %). The electron beam qualities required for fs facility operation (longitudinal emittance 10 π keV-mm, normalized transverse emittance 2π mm-mrad, charge 0.1 nC) can be met with laser-driven rf-gun. After the exit of the undulator (number of periods $N_{\mathrm{w}} \simeq 250$) the spontaneous undulator radiation enters the angular filter, which select power radiated in the central cone. After filter the frequency chirped soft X-ray pulse enters the monochromator with resolution $\Delta\omega/\omega \simeq N_{\mathrm{w}}^{-1} \simeq 4 \times 10^{-3}$. It will provide radiation pulses with 30 fs (FWHM) duration. On the basis of the TTF linac parameters it should be possible to achieve an average brilliance of 10^{14} photons $\mathrm{s}^{-1}\mathrm{mrad}^{-2}\mathrm{mm}^{-2}$ per 0.1 % BW in the photon energy range 50-200 eV. The average number photons at the monochromator exit (at monochromator efficiency 10 %) can exceed 10^5 photons within 30 fs pulse duration. The pulse duration can be tuned from 30 to 160 fs by changing the resolution of monochromator.

Preprint submitted to *4 January 2095*

1 Introduction

Phase transitions, surface processes, and chemical reactions are ultimately driven by the motion of atoms on the time scale of one vibration period ($\simeq 100$ fs). The pulse length of existing synchrotron sources is too long for resolving atomic motion on the 100 femtosecond time scale. Recent efforts at applying 300 fs X-rays pulses to probe structural dynamics have used a synchrotron radiation source combined with a femtosecond optical quantum laser [1]. The same technique can be used to generate in the future 100 fs X-ray pulses with an average brilliance of 10^{11} photons $\mathrm{s}^{-1}\mathrm{mrad}^{-2}\mathrm{mm}^{-2}$ per 0.1 % BW at the photon energy of 2 keV [1].

New proposal of femtosecond soft X-ray facility, which is described in this paper, is based on frequency chirping of the undulator spontaneous radiation pulse. Using spatial and spectral filtering we can reduce the duration of the synchrotron radiation pulse to about 10 fs. A correlated frequency distribution along the radiation pulse can be obtained by changing the electron energy along the electron bunch, i.e. chirping the electron bunch energy before it enters the undulator. The main ingredients of a femtosecond X-ray facility are a high energy electron beam with small longitudinal emittance. A small (close to diffraction limited) transverse emittance, is needed too.

The stringent electron beam qualities required for femtosecond synchrotron radiation facility can be met with linac as a driver. There are several factors in favor of linacs. In order to achieve femtosecond pulse duration, a high quality of sub-picosecond energy chirped electron beam is needed, which is difficult to obtain in a storage ring because of instabilities. The key to achieving low emittance in linac is therefore the source, the electron gun and linac structure that preserves this transverse and longitudinal properties during acceleration. The research and progress in the technology and accelerator physics of linear colliders have produced the tools and knowledge necessary to control wakefields in order to achieve linac acceleration with minimal longitudinal and transverse emittance dilution. RF photoinjectors have been developed as the most effective method of achieving very high quality electron pulses. Accelerating the beam off crest of the rf waveform in the linac creates an energy-phase correlation that can be used in femtosecond synchrotron radiation facility. The duration of electron pulse produced by the low emittance gun is of about a few picoseconds, and is still not short enough to reach the 10 fs X-ray pulses within an undulator of a reasonable length. The way out is to compress the bunches longitudinally at an ultra-relativistic beam energy where space charge forces are reduced drastically. This can be achieved with a bunch compressor chicane. The purpose of the compressors is to reduce the bunch length, thereby increasing the local energy spread to a level limited undulator radiation bandwidth.

In 1999 Pellegrini analyzed the possibility of producing femtosecond long pulses by chirping and compressing (in grating compressor) the output X-ray SASE FEL radiation [2]. In this paper we extend this approach for generation of short pulses of spontaneous radiation. This becomes possible due to application of an angular filter and use of grating monochromator.

In this paper we analyze a possibility for integration of femtosecond synchrotron radiation source into the TESLA Test Facility (TTF) being under construction at DESY. A 1 GeV superconducting linear accelerator at the TTF is capable to produce electron beam with high average and peak power, low energy spread and emittance. The main practical application of this accelerator is to use it for driving the soft X-ray SASE FEL [3–5]. Parameters of photoinjector, bunch compression system, high total voltage (1.2 GV) and relatively large duty factor (1%) makes the TTF acceleartor to be a unique driver not only for FELs, but also for spontaneous radiators. With the addition magnetic bunch compressor, the TTF linac is capable to produce 160 fs (FWHM) electron bunches with an energy of 500-700 MeV, normalized emittance 2π mm-mrad, local energy spread 0.5 MeV, charge 0.1 nC, and energy chirp 1 %. A transfer line takes the beam and matches it to the entrance of a 7-m-long undulator. After leaving the undulator, the electron beam is deflected onto a beam dump, while the photon beam enters the angular filter, which select power radiated in the central cone. After filter the frequency chirped soft X-ray pulse enters the monochromator which selects the radiation from the bunch slice. It will provide soft X-ray pulses with 30 fs (FWHM) duration. On the basis of the TTF linac parameters it should be possible to achieve an average brilliance of 10^{14} photons $\mathrm{s}^{-1}\mathrm{mrad}^{-2}\mathrm{mm}^{-2}$ per 0.1 % BW in the photon energy range 50 - 200 eV. The average number photons at the monochromator exit (at monochromator efficiency 10 %) can exceed 10^5 photon within the pulse of 30 fs duration. The pulse duration can be tuned from 30 to 160 fs by changing the resolution of monochromator (by means of changing the spectral window). The proposed source provides wide possibilities to control and modify the shape of the chirped radiation pulse through spectral filtering (using different mask functions). For example, closely spaced fs pulses obtained through spectral filtering are particularly interesting for many applications.

Here it is relevant to compare the technical challenges of TTF linac-based soft X-ray SASE FEL and soft X-ray femtosecond synchrotron radiation source. Based on the requirements for a femtosecond synchrotron source, the design goal of rf photocathode gun is a 6-ps-(rms)-long beam of 0.1 nC charge with a normalized transverse rms emittance of 2π mm-mrad and longitudinal emittance 10 π KeV-mm. Design goal for soft X-ray SASE FEL is a beam of 1 nC charge with the same emittances. Comparing the beam parameters we can conclude that to make preservation of the emittances in the case of the SASE FEL parameters is more difficult, since in our case the charge is about an order of magnitude smaller. The SASE process starts from spontaneous emission and grows exponentially along the undulator until saturation. Usually this occurs after about 10 exponential field gain length. As a result, the output power of

SASE FEL decreases drastically at the bunch charge decrease, or at the emittance growth. If we consider the femtosecond synchrotron radiation source, we find that the number of photons per pulse and time resolution evolve slowly with charge and emittance. This is a result of spontaneous emission.

2 Principle of operation

2.1 Characteristics of undulator radiation

Let us introduce the basic features of undulator radiation. The undulator equation

$$\omega = 2ck_{\mathrm{w}}\gamma^2 \left[1 + \frac{K^2}{2} + \gamma^2\theta^2\right]^{-1}$$

tell us the frequency of radiation as a function of undulator period $\lambda_{\mathrm{w}} = 2\pi k_{\mathrm{w}}$, undulator parameter K, electron energy $E = m_0c^2\gamma$, and polar angle of observation θ. Note that for radiation within the cone of half angle

$$\theta_{\mathrm{cen}} = \frac{\sqrt{1 + K^2/2}}{\gamma\sqrt{N_{\mathrm{w}}}} \ ,$$

the relative spectral FWHM bandwidth is $\Delta\omega/\omega = 0.88/N_{\mathrm{w}}$, where N_{w} is the number of undulator periods. The spectral and angular density of the radiation energy emitted by a single electron during the undulator pass is given by the expression (at zero angle):

$$\frac{\mathrm{d}^2\,\mathcal{E}}{\mathrm{d}\,\omega\,\mathrm{d}\,\Omega} = \frac{e^2N_{\mathrm{w}}\gamma^2A_{\mathrm{JJ}}^2K^2}{2c(1+K^2/2)^2}\frac{\sin^2[\pi N_{\mathrm{w}}(\omega-\omega_0)/\omega_0]}{[\pi N_{\mathrm{w}}(\omega-\omega_0)/\omega_0]^2} \ .$$

Here $\omega_0 = 2\gamma^2k_{\mathrm{w}}/(1+K^2/2)$ is resonance frequency, $A_{\mathrm{JJ}} = [J_0(Q) - J_1(Q)]$, where J_n is the Bessel function of nth order, and $Q = K^2/(4+2K^2)$. Now we would like to calculate the energy radiated into the central cone. In the small-angle approximation the solid angle is equal to $\mathrm{d}\,\Omega = \theta\,\mathrm{d}\,\theta\,\mathrm{d}\,\varphi$. Integration of spectral and angular density over ω and φ gives us factors ω_0/N_{w} and 2π, respectively. We also have to integrate over θ from 0 to θ_{con}. Thus, the energy radiated into the central cone by single electron is given by

$$\Delta\mathcal{E}_{\mathrm{cen}} \simeq \frac{\pi e^2A_{\mathrm{JJ}}^2\omega_0K^2}{c(1+K^2/2)} \ .$$

Individual positions of electrons in the bunch are random, thus the radiated fields due to different electrons are uncorrelated, and the average energy radiated by the bunch is a simple sum of the radiated energy from the individual electrons.

Beyond the natural broadening, due to the finite number N_w of oscillations, further spectral broadening can be incurred with the passage of many electrons through the undulator in a bunch of finite size, divergence, and energy spread [7]. If there is an electron energy (rms) spread within the bunch, $\Delta\gamma/\gamma$, there will be a corresponding photon energy spread given by $\Delta E_\mathrm{ph}/E_\mathrm{ph} = 2\Delta E/E$, where the factor of two is due to the square relationship between photon energy and electron energy. A more significant effect is that due to angular distribution within the bunch. As a result, some electrons traverse the undulator not along or parallel to the z-axis, but at a small angle $\theta_{x,y}$. These electrons undergo the same number N_w of oscillations, but experience a somewhat longer period $\lambda_\mathrm{w}/\cos(\theta_{x,y})$. If there is an rms angular divergence σ' within the bunch, there will be a corresponding photon energy spread given by $\Delta E_\mathrm{ph}/E_\mathrm{ph} = \gamma^2(\sigma')^2/(1+K^2/2)$. In what follows we use the following assumption:

$$4\frac{\Delta E}{E} \ll \frac{1}{N_\mathrm{w}} , \quad (\sigma')^2 \ll \frac{1+K^2/2}{\gamma^2 N_\mathrm{w}} . \tag{1}$$

When these conditions are satisfied, the energy spread and angular divergence cause a spectral broadening less than $1/N_\mathrm{w}$ and central cone will be rather well defined in terms of both its angular definition and spectrum.

To complete the undulator characteristics calculation an expression is needed for photon flux within the central cone. To wright this we divide radiated energy by the energy per photon $\hbar\omega_0$, and obtain

$$\frac{\mathrm{d}\,N_\mathrm{cen}}{\mathrm{d}\,t} = \frac{\pi\alpha A_\mathrm{JJ}^2 K^2 N_\mathrm{e} f}{1+K^2/2} ,$$

where $\alpha = 1/137$ is fine-structure constant, N_e is the number of electrons in a bunch, f is the bunch repetition rate.

2.2 Spectral brightness of undulator radiation

The quality of the radiation source is described usually by the spectral brightness defined as the density of photons in the six-dimensional phase space volume [6]:

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

where $\sigma_{x,y}$ and $(\sigma_{x,y})'$ are the (horizontal and vertical) photon beam Gaussian $(1/\sqrt{e})$ radius and Gaussian half angle respectively. In the case of finite particle beam emittance the photon brightness is reduced. The amount of reduction, however, depends on the matching to the photon beam. The particle beam parameters are

$$(\sigma_{\rm e})_{x,y}^2 = (\epsilon_{\rm e})_{x,y}\beta_{x,y} \ , \quad (\sigma'_{\rm e})_{x,y}^2 = (\epsilon_{\rm e})_{x,y}/\beta_{x,y} \ ,$$

where $\beta_{x,y}$ is the betatron function in the undulator, $\epsilon_{x,y}$ is the horizontal and vertical electron beam emittance, respectively. To modify the expression for spectral brightness to the case of undulator radiation, we can use the previously calculated photon flux in the central radiation cone, $\mathrm{d}\,N_{\rm cen}/\,\mathrm{d}\,t$, which was defined as having a relative spectral bandwidth (BW) of $\Delta\omega/\omega_0 = 1/N_{\rm w}$ (under condition (1)) and radiation cone of half angle $\theta_{\rm cen}$. Taking into account contribution of diffraction effects, we may wright the following expressions for the size and angular divergence of the photon beam:

$$(\sigma_{\rm tot})_{x,y}^2 = (\sigma_{\rm e})_{x,y}^2 + \sigma_{\rm d}^2 \ , \quad (\sigma'_{\rm tot})_{x,y}^2 = (\sigma'_{\rm e})_{x,y}^2 + (\sigma'_{\rm d})^2 \ ,$$

where $\sigma_{\rm d} = \sqrt{\lambda L_{\rm w}/(8\pi^2)}$ is the diffraction limited radiation beam size, $\sigma'_{\rm d} = \sqrt{\lambda/(2L_{\rm w})}$ is the diffraction limited radiation beam divergence, and $L_{\rm w}$ is the undulator length [6]. It is frequently used in the synchrotron radiation community to express the spectral brightness in terms of relative spectral bandwidth of 10^{-3}. Expression for B in terms of photon flux within the central cone is [7]:

$$B = \frac{(\mathrm{d}\,N_{\rm cen}/\,\mathrm{d}\,t)(N_{\rm w}/1000)}{4\pi^2(\sigma_{\rm tot})_x(\sigma_{\rm tot})_y(\sigma'_{\rm tot})_x(\sigma'_{\rm tot})_y}\frac{\rm photons/s}{\rm mm^2 mrad^2 (0.1\%BW)} \ .$$

2.3 Spatial and spectral filtering of undulator radiation

The limiting condition of spatially coherent radiation is a space-angle product $d\cdot\theta = \lambda/(2\pi)$, where d is a Gaussian $1/\sqrt{e}$ diameter and θ is the Gaussian half angle [7]. In general case the phase space volume of photons in central radiation cone is larger than the limiting condition required for spatial coherence. Thus, for experiments that require spatial coherence, a pinhole and angular acceptance aperture are to be introduced. This pinhole spatial filter is used to narrow, or filter, the phase space of transmitted radiation. Filtering to $d\cdot\theta = \lambda/(2\pi)$ requires to use of both a small pinhole (d), and some limitation on θ, such that the product is equal to $\lambda/(2\pi)$.

Radiation is transversely coherent when

$$(\sigma_{\rm e})_{x,y}(\sigma'_{\rm e})_{xy} \ll \lambda/(4\pi) \ , \quad \beta \simeq L_{\rm w} \ .$$

Under this conditions, one has $(\sigma_{x,y})^2 \ll (\sigma_{\rm d})^2$ and $(\sigma'_{x,y})^2 \ll (\sigma'_{\rm d})^2$ and spectral-angular dependence of the radiation emitted by an electron beam can be approximated as spectral-angular dependence of the radiation emitted by a single electron. This limit corresponds to maximum of brilliance

$$B = \frac{4(\mathrm{d}\,N_{\mathrm{cen}}/\,\mathrm{d}\,t)(N_{\mathrm{w}}/1000)}{\lambda^2}\frac{\mathrm{photons/s}}{\mathrm{mm^2mrad^2(0.1\%BW)}} \ .$$

When the electron beam emittance is large,

$$(\sigma_{\mathrm{e}})_{x,y}(\sigma'_{\mathrm{e}})_{xy} \gg \lambda/(4\pi) \ ,$$

the radiation is partially coherent. One can find that the influence of electron beam divergence on the properties of the undulator radiation can be neglected when the beta-function is large enough. In the region of parameters when

$$(\sigma'_{x,y})^2 < (\sigma'_{\mathrm{d}})^2$$

a downstream diaphragm of aperture $d = 2\sigma_{\mathrm{d}}$ is used for selection of the transversely coherent fraction of undulator radiation. Finally, in this limit, the flux of transversely coherent photons into the bandwidth $\Delta\omega/\omega = 0.1\%$ can be estimated simply as

$$\frac{\mathrm{d}\,N_{\mathrm{ph}}}{\mathrm{d}\,t} \simeq \frac{\lambda^2 B}{4} \ .$$

2.4 Shortening through spectral filtering

The layout of the soft X-ray femtosecond facility is presented in Fig. 1. An ultrarelativistic electron bunch passes an undulator and radiates a pulse of spontaneous undulator radiation. Soft X-ray pulse shortening is achieved in a two-step process sketched in Fig. 2. In the first step a frequency chirping is impressed on the radiation pulse which can be obtained by changing the electron energy along the electron bunch, i.e. chirping the electron bunch energy before it enters the undulator. Optimum undulator performances obtained with small electron beam divergence and local energy spread (conditions (1) are fulfilled). The angular acceptance aperture is used for selection of the fraction of undulator radiation within the central cone. When this radiation is partially coherent a downstream diaphragm is used for selection of the transversely coherent fraction of undulator radiation which is directed to the monochromator. The second step is the shortening (or shaping) through spectral filtering. This technique consists of manipulating the pulse spectrum. The pulse to be shortened is spectrally dispersed using grating. The spectrum is propagated through an exit slit which spectrally filters the pulse. The resolution of the monochromator is equal to $\Delta\omega_{\mathrm{m}}$, the central frequency is equal to ω_0 and $\Delta\omega/\omega_0 < 1/N_{\mathrm{w}}$. The shortest pulse durations $\Delta\tau$ that can be obtained are determined (at fixed number of undulator periods and under condition (1)) by the finite duration of the input pulse τ_0 (FWHM) and bunch energy chirp $\pm\delta E/E$:

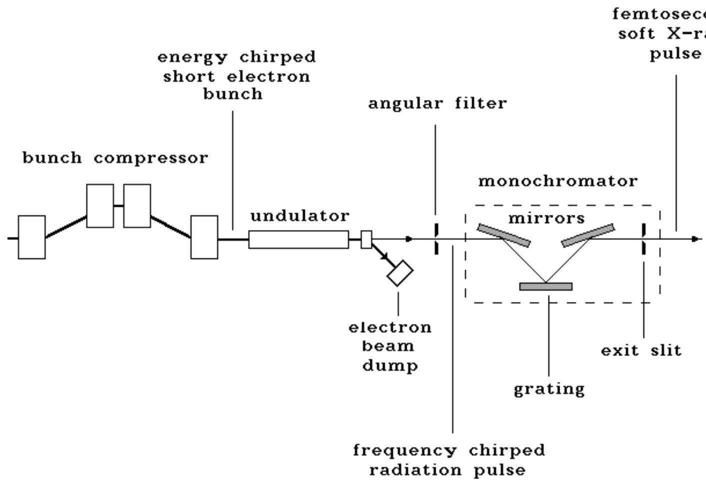

Fig. 1. Basic scheme of the soft X-ray femtosecond facility

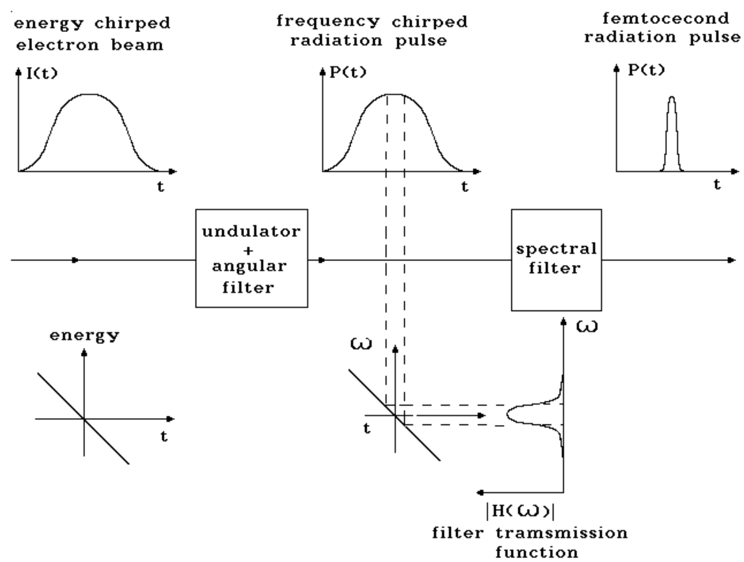

Fig. 2. Sketch of femtosecond soft X-ray pulse synthesation through frequency chirping and spectral filtering

$$\Delta\tau \simeq \tau_0/(4N_\mathrm{w}\delta E/E) \ .$$

If there is an rms local energy spread ΔE within the bunch, the shortest pulse duration can be approximated by

$$\Delta\tau \simeq \tau_0/(4N_\mathrm{w}\delta E/E) + \tau_0\Delta E/\delta E \ . \qquad (2)$$

It is clear that at fixed longitudinal emittance of electron bunch, the second term is not a τ_0 dependent quantity.

Table 1
Parameters of the TTF linac-based femtosecond facility

Electron beam	
bunch energy, MeV	500 - 700
bunch charge, pC	100
rms local energy spread, %	0.1
rms incoming energy spread, %	1
final rms bunch length, μm	20
normalized emittance, π mm-mrad	2
number of bunches per train	7200
bunch spacing, ns	111
repetition rate, Hz	10
Undulator	
Type	planar
number of periods	250
period, cm	2.7
min. gap, mm	12
max. peak field, T	0.5
external beta-function, m	3
Grating monochromator	
resolution, %	0.4
efficiency, %	10
wavelength range, nm	50 - 200
Output radiation	
wavelength, nm	50 - 200
min. pulse duration, fs (FWHM)	30
number of photos per pulse	10^5
spectrum width, % (FWHM)	0.4

3 Numerical example

The operation of linac-based femtosecond synchrotron radiation facility is illustrated for the TESLA Test Facility (TTF) which is under construction at DESY. Table 1 lists some of the basic parameters of the electron beam, undulator, monochromator, and output radiation. We assume to use of a planar undulator with 250 periods. The radiation wavelength can be changed either by changing the electron beam energy and additionally by changing the undulator magnet gap (thereby changing K). For the chosen undulator period (2.7 cm) the maximum value of undulator parameter is $K_{\max} = 1.3$. The corresponding peak magnetic field on the undulator axis is 0.5 T. The minimal gap corresponding to $K_{\max}$ is equal to 12 mm. Fig. 1 illustrates how the technique is used to obtain spatially coherent radiation from the undulator. Only the angular acceptance aperture is introduced. For undulator with 250 periods, a monochromator and beamline optics, with an overall efficiency η of 10 % (30 % grating efficiency and five glancing incidence mirrors at 0.8 reflectivity each) are used to obtain $\Delta\omega/\omega \simeq 4 \times 10^{-3}$. In this case we have $\delta E/E \simeq 1\%$

Table 2
Parameters of the 2nd bunch compressor double chicane

Parameters	Symbol	Unit	Value
bunch energy	E	MeV	500
bunch charge	Q	pC	100
initial rms bunch length	σ_z	μm	400
final rms bunch length	σ_z	μm	20
rms incoming energy spread	$\delta E/E$	%	1
net momentum compaction	R_{56}	mm	34
total system length	L_{tot}	m	35
length of each dipole magnet	L_{B}	m	1.5
drift between 1st two (last two) dipoles	ΔL	m	3.4
drift between center two dipoles	ΔL_{c}	m	0.5
bend angle for each of 1st four dipoles	θ_{B1}	deg	3.4
bend angle for each of last four dipoles	θ_{B2}	deg	1.3
magnetic field for each of 1st four dipoles	H_1	G	660
magnetic field for each of last four dipoles	H_2	G	250
emittance dilution due to CSR	$\Delta\epsilon/\epsilon$	%	1.5
rms CSR energy spread	$\Delta E_{\mathrm{CSR}}/E$	%	0.03

and $\Delta E/E \simeq 0.1\%$ and, according to (2), the minimum soft X-ray pulse duration reaches a value about 30 fs (FWHM). The average number of photons at the monochromator exit can exceed 10^5 photons per 30-fs duration pulse. An average brilliance would be about 10^{14} photons $\mathrm{s}^{-1}\mathrm{mrad}^{-2}\mathrm{mm}^{-2}$ per 0.1 % BW. The femtosecond facility at TTF is designed to be tunable in the photon energy range 50-200 eV, corresponding to the 500-700 MeV electron energy and 0.2-0.5 T undulator field. The value of the average brilliance of such a femtosecond soft X-ray facility can be as high as the values of the average brilliance reached by a medium-size synchrotron light sources. Let us present a specific numerical example for the case of an undulator (U-XUV1) at storage ring DORIS. The average brilliance at a photon energy around 100 eV is about to 4×10^{14} photons $\mathrm{s}^{-1}\mathrm{mrad}^{-2}\mathrm{mm}^{-2}$ per 0.1 % BW. Note that monochromator provides spatially and spectrally filtered radiation pulse.

4 TTF linac as a driver for femtosecond facility

The proposed phase bunching system is sketched in Fig. 3. Compressing the bunch will be done in stages to avoid space charge and coherent synchrotron radiation (CSR) and other wakefield effects limiting the achievable bunch length and transverse emittance. The first compression is from 1.6 mm to 400 μm (rms). It consists of a 150 MeV accelerating module followed by the first TTF magnetic chicane generating R_{56} needed for bunch compression [8]. Calculations show that induced energy spread and emittance dilution should

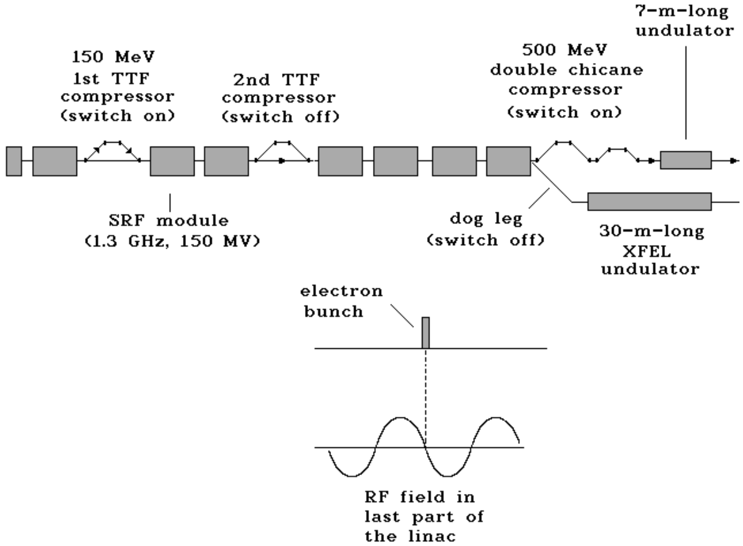

Fig. 3. TTF femtosecond facility compression and acceleration schematic

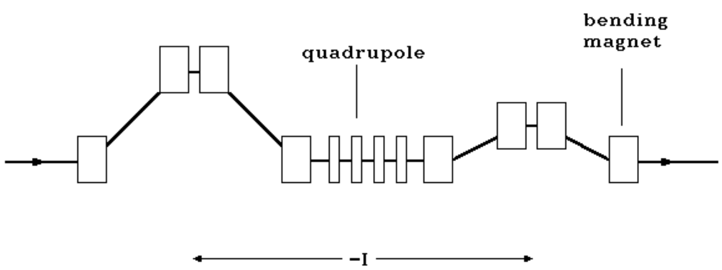

Fig. 4. Schematic of the double chicane bunch compressor

not be a serious limitation in BC1 at 100 pC bunch charge. After leaving the first bunch compressor the electron bunch of 400 μm 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 accelerating structure at 90° crossing phase. Our analysis shows that adequate solution for the BC2 design is a double chicane (see Fig. 4). The requirements for the magnetic bunch compressor in our case are very close to those for the magnetic bunch compressor BC2 in the Linac Coherent Light Source (LCLS) project [9]. Each chicane is twelve meters long and contains for a C-type bending magnets. The first and second chicanes generate $R_{56} = 31$ mm and 3 mm at $\theta_{\mathrm{B1}} = 3.4°$ and $\theta_{\mathrm{B2}} = 1.3°$ respectively. Four quadrupoles are placed between the chicanes in locations where the dispersion passes through zero. Since the energy spread generated by CSR is correlated along the bunch, its effect on the transverse emittance can be compensated in a double chicane with optical symmetry to cancel the longitudinal-transverse coupling [9]. Calculations of the CSR induced emittance dilution which includes field transients, bend-to-bend radiation and radial forces show a net BC2 emittance dilution of 2 %

with CSR induced energy spread of 0. 03 % (at 100 pC charge per bunch). Table 2 summarizes the proposed design parameters for BC2 providing bunch compression from 400 to 20 μm (rms). In this case the parameters of bunch compressor are practically identical to those for BC2 compressor designed at SLAC in the framework of LCLS project [9].

Acknowledgments

We thank J.R. Schneider and D. Trines for interest in this work.

References

[1] R. W. Schoenlein et al., Science 287(2000)2237

[2] C. Pellegrini, Nucl. Instrum. and Methods A 445(2000)124

[3] J. Rossbach, Nucl. Instrum. and Methods A 375(1996)269

[4] J. Feldhaus et al., Optics Communications 140(1997)341

[5] "Seeding Option for the VUV Free Electron Laser at DESY": Proposal. Available at DESY by request only

[6] H. Wiedemann, "Particle Accelerator Physics" (Springer, Berlin, 1995)

[7] D. Attwood, "Soft X-ray and Extreme Ultraviolet Radiation" (Cambridge University Press, 1999)

[8] M. Dohlus, A. Kabel, and T. Limberg, Nucl. Instrum. and Methods A 445(2000)84

[9] The Linac Coherent Light Source (LCLS) Design Study Report, SLAC-R-521, 1998