Development of a Femtosecond Soft X-ray SASE FEL at DESY

W. Brefeld [a], B. Faatz [a], J. Feldhaus [a], M. Körfer [a], J. Krzywinski [b], 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 describe the extension of the soft X-ray SASE FEL at the TESLA Test Facility (TTF) at DESY for generation of femtosecond pulses. The proposed scheme operates as follows. The first stage is a conventional FEL amplifier seeded by 523 nm external laser. A zero area optical pulse (i.e. the pulse with zero value of optical field in the central area of the pulse) is timed to overlap with the electron bunch. Radiation power is amplified up to the saturation level. Following the first stage the electron beam enters the main 6 nm SASE undulator. Large energy spread is induced in the significant fraction of the electron beam due to the FEL interaction process, and only a small part of the electron bunch (near the center of zero area light pulse) is capable to produce radiation in the 6 nm SASE FEL. The SASE FEL described in this paper will provide soft X-ray pulses with 30 fs (FWHM) duration. On the basis of the TTF parameters it should be possible to achieve an average brilliance of 10^{22} photons $s^{-1}mrad^{-2}mm^{-2}$ per 0.1% BW. The average number of photons can exceed 10^{12} photon/pulse.

1 Introduction

Phase transitions, surface processes, and chemical reactions are ultimately driven by the motion of atoms on the time scale of one vibrational period ($\simeq$ 100 fs). Unfortunately, the pulse length of present synchrotron light 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 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

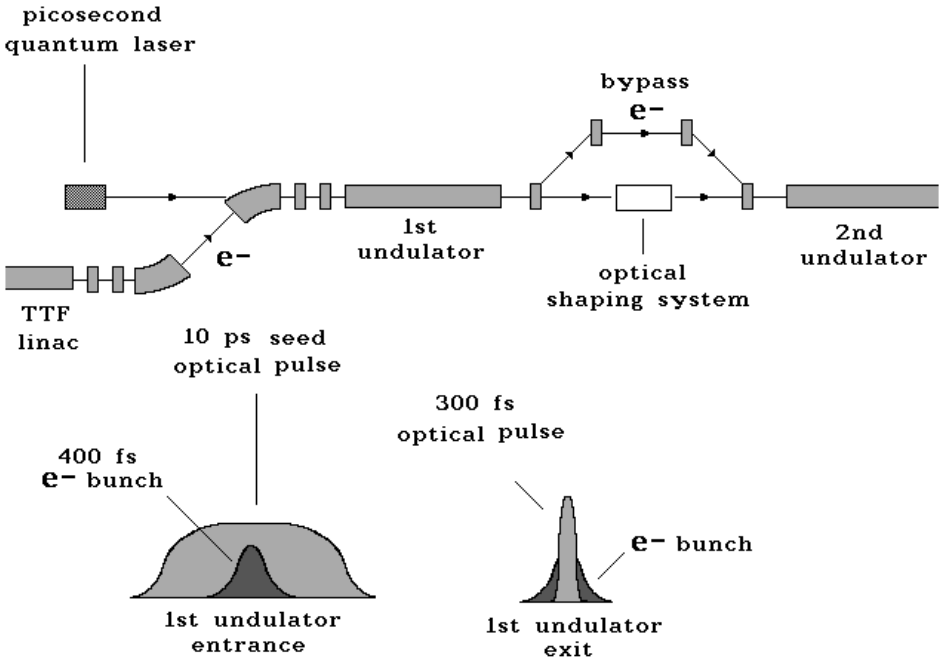

Fig. 1. The two stage scheme of the seeding system

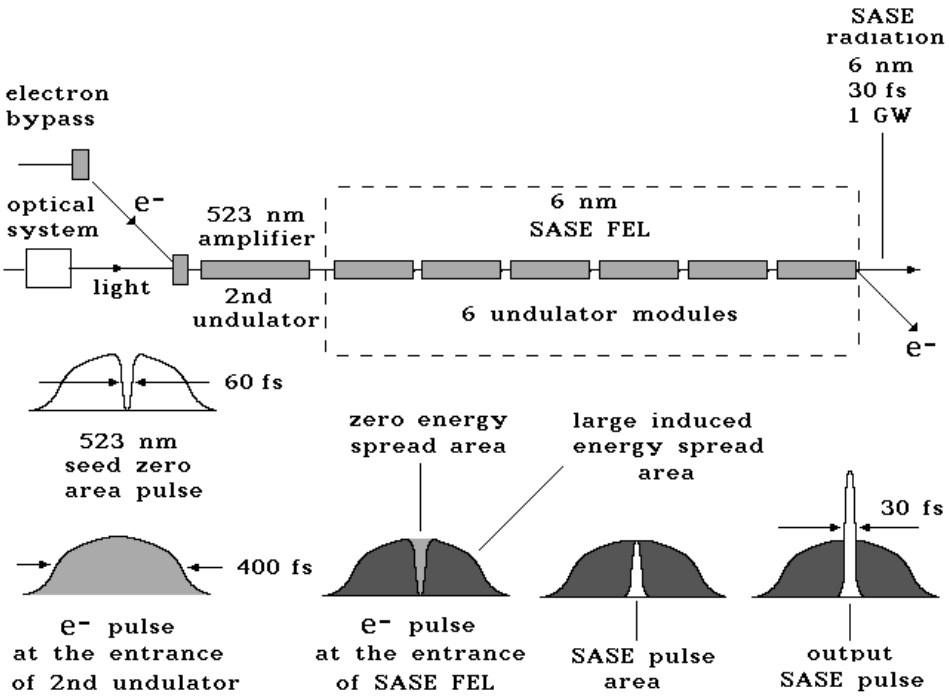

Fig. 2. Schematic diagram of zero area pulse technique for the generation of the soft X-ray femtosecond SASE pulses

brilliance of 10^{11} photons $s^{-1}mrad^{-2}mm^{-2}$ per 0.1% BW at the photon energy of 2 keV [1].

Femtosecond soft X-ray facility proposed in this paper is based on the use of soft X-ray SASE FEL. To be specific, we illustrate a new method of femtosecond X-ray pulses production with an example for the SASE FEL at the TESLA Test Facility (TTF) being under construction at DESY. The idea for production of very short X-ray pulses is based on a high sensitivity of the FEL gain on the energy spread in the electron beam. Thus, a technique best suited for the femtosecond SASE FEL consists of "manipulating" the energy spread along the electron bunch. The required shaping of the energy spread is performed by passing the electron beam trough two-stage FEL amplifier (see Fig. 1) seeded by an optical pulse from existent TTF laser facility (pulse duration 10 ps, optical energy in the pulse 0.3 μJ, wavelength 523 nm – the 2nd harmonic of Nd:YLF laser). The first stage of the FEL amplifier operates in the linear regime and produces optical pulses of 300 fs pulse duration with peak power of about 60 kW which is strictly synchronized with the electron bunch. After the exit of the first stage the electron bunch is guided through a bypass, and the radiation enters the pulse shaping system. The functions of the electron bypass are to provide equal time delays for the electron and the light beams, and to suppress microbunching induced in the electron bunch in the first undulator due to the FEL process. The function of the optical pulse shaping system is to prepare zero area optical pulse. In pulse shaping system the input radiation is focused into a single-mode optical fiber. After the fiber exit, the linear chirped pulse is sent through spectral filtering system. The pulse is spectrally dispersed using a grating and directed through a mask which spectrally filters the pulse. The spectral components are recollimated into a beam by a second grating. The shaping system produces zero area pulses which are strictly synchronized with electron bunches at the entrance to the second undulator. Since the input optical pulse is produced by the same electron bunch, the proposed scheme tolerates electron pulse time jitter of about a few picoseconds. A zero area optical pulse produced by the shaping system is amplified up to the saturation level in the second undulator. Large energy spread is induced in the significant fraction of the electron beam due to the FEL interaction process, and only a small part of the electron bunch (near the center of the zero area light pulse) is capable to produce radiation in the 6 nm SASE FEL (see Fig. 2).

2 Scientific opportunities with the femtosecond soft X-ray SASE FEL

To date, the study of ultrafast dynamics in the field of physics, chemistry, and biology has relied largely on femtosecond optical pulses in the visible or infrared spectral range. Using fs optical lasers researches could collected a wealth on information on the details of reaction pathways in many molecular systems e.g. J_2, CH_2J_2, and even larger systems [3]. The importance of the field is underlined by awarding the Nobel Prize in chemistry to A. Zewail. Since all information in optical fs-experiments is obtained from spectroscopic results, e.g. ionization probability or kinetic energy of photoelectrons, a detailed knowledge on the involved - sometimes rather complex - energy surface is required for the interpretation and understanding

of the experimental data. Soft X-rays have several advantages compared to optical light pulse. Thanks to the element specific absorption of inner shell electrons well-defined atoms can be excited selectively. Moreover, chemical bonds can be selected by their well-known chemical shift, e.g. in inner shell photoelectron spectra (XPS). The latter can be used in order to identify surface and bulk states of condensed matter. Finally, the local excitation of tightly bound core levels allows the determination of structural information with various techniques (EXAFS, XANES, and photoelectron diffraction). Therefore, fs soft X-ray pulses hold great promises for new and exciting experiments in many fields of research which will give deep insight into the dynamics of nuclei and electrons on the time scale of vibrational motion.

The vibrational period of nuclear motion depends on the strength of chemical bonds and the mass of nuclei. In heavy molecules like J_2 the period is approximately 100-200 fs while for light molecules, especially hydrogen containing molecules it last about 10-50 fs. It is thus obvious, that the proposed new design for a soft X-ray FEL with 30 fs long pulses will have a considerable advantage compared to other proposed schemes [4,2] – some are already under construction or have emitted first light [5] - since their pulse duration of 200-300 fs is just at the limit for the studies on nuclear motion and lattice vibrations. Pump probe techniques which are commonly used with optical lasers, are highly desirable in order to make full use of the short pulses. Since precise timing is needed with a jitter of less than 30 fs we suggest to combine the proposed fs soft X-ray FEL with UV optical pulses generated in an additional undulator using the same electron beam as outlined in ref. [6].

Time resolved experiments with 30 fs resolution will open new scientific opportunities in chemistry, molecular physics, solid state physics and surface science. The use of pump-probe techniques will allow the study of vibrational and bond breaking and dissociation in complex molecules with element selectivity. Thanks to the local excitation it will be possible to distinguish the vibrational motion of non-equivalent atoms, e.g. the central and the terminal nitrogen atom in N_2O. Moreover, time resolved photoemission (XPS) can be used to ascertain decay rates and vibrational periods in well-defined subgroups in large molecules, since the chemical shift in the XPS spectrum is a fingerprint of chemical bonds.

In a similar way, research on clusters and nanocrystals will benefit from the proposed FEL. As a result of their small size a large fraction of atoms are located at the surface. Time resolved studies (pump-probe) will allow the investigation of surface and bulk states separately. Furthermore, photon induced reactions, phase transitions and electron transfer processes can be studied on a time scale of a few ten fs. Photoelectron, ion and fluorescence signals as well as combinations (electron ion: PEPICO, ion-ion, PIPICO, for the study of fragmentation and dissociation) can be used as a monitor. Metal, semiconductor and covalently bound systems, and complexes that play an important role in atmospheric processes are great interest in this context.

The element specific excitation of soft X-rays will allow the study of photodynamical processes of individual atoms and molecules on surfaces. Time resolved EXAFS/XANES or photoelectron diffraction making use of two colour pump- and probe techniques will give information on the motion (vibration dissociation) on well characterized surfaces in real time. The reaction dynamics of adsorbates is of major importance for the understanding of chemical processes at surfaces and an important issue in this context. Catalytic reactions of metal and semiconductor interfaces are of particular interest. UV light can induce a chemical reaction like oxidation, which can be studied by looking at reaction products on a fs time scale. The high photon density of the FEL beam - especially when focussed into a small spot - will result in efficient photodesorption and plasma formation. Many processes occurring in laser induced plasma going on in the plume are not well understood. Detailed information can be obtained using two-colour pump probe experiments and detecting photoelectrons and ions ejected from the plasma plume. Photoreactions and phase transition in bulk samples can be investigated with time resolved X-ray emission spectroscopy. The mean free path length of soft X-rays is much larger than the internuclear separations in solids. Thus, time resolved studies of bulk properties, the dynamics of atoms doped into solids and photoinduced reactions at buried interfaces become feasible.

All applications outlined above are based on 30 fs long soft X-ray pulses. One can expect that first successful experiments in this field will stimulate further applications.

3 Description of femtosecond X-ray FEL at the TESLA Test Facility

Present design assumes to use project parameters of the TESLA Test Facility accelerator [2]. Facility for production of femtosecond SASE X-ray pulses consists of a two-stage seeding system operating at the wavelength of 523 nm. Figure 1 shows a schematic diagram of a seed system for the femtosecond soft X-ray SASE FEL at the TESLA Test Facility. The scheme consists of seed quantum laser, two undulators and optical pulse shaping system located between them. The first undulator operates in a linear regime and produces short light pulse (of about 300 fs duration) synchronized with the electron bunch. After the exit of the first undulator the electrons are guided through a bypass and the radiation enters the shaping system. A zero area light pulse with peak power of about 10 kW is generated by pulse shaping system. This radiation pulse is amplified up to the saturation level in the second undulator. At the exit of the second undulator the most fraction of the electron bunch has large energy spread due to the FEL process except of a small region in the center of zero pulse area. This of the essence of the energy spread shaping technique. The process of amplification of radiation in the X-ray undulator develops in the same way as in conventional SASE FEL: fluctuations of the electron beam current density serve as the input signal. The seeding radiation (523 nm wavelength) does not interact with the electron beam in the X-ray undulator and is

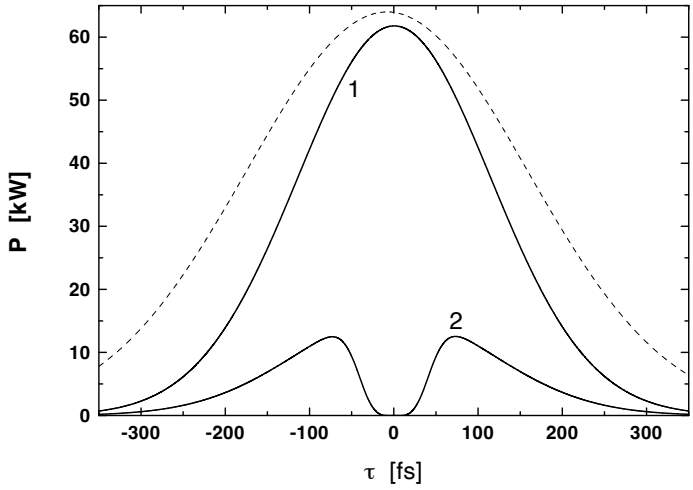

Fig. 3. Temporal profile of the radiation pulse at the exit of the first stage of 523 nm FEL amplifier (curve 1). Curve 2 present temporal profile of the radiation pulse after optical pulse shaping system. Dotted line denotes current profile of the electron bunch.

diffracted out of the electron beam. Since the gain of the FEL amplifier is very sensitive to the energy spread, only this small part of the electron bunch produces the radiation, thus providing short pulse duration (see Fig. 2). For ultrashort zero area of seed optical field, the slippage of radiation with respect to the electron bunch in the 523 nm high-gain FEL amplifier can be an essential mechanism for shortening the SASE radiation pulse. Starting with zero area of optical field of 60 fs duration (FWHM) we can obtain 30 fs (FWHM) pulses at the wavelength of 6 nm.

An attractive feature of this scheme is the absence of no apparent limitations which would prevent operation at even SASE pulse with duration close to coherence time (about 2 fs in our case). For example close to end of 523 nm FEL operation (i.e. close to saturation) we can use a magnetic delay to position the 523 nm radiation near the tail end of undisturbed part of the bunch. An experimenter can easily control the duration of "zero" area by tuning the magnetic field in the shifter (a three-dipole chicane). In this technique we use zero are of seed optical field that is much longer than the produced soft X-ray SASE pulse.

The function of the first stage of 523 nm FEL amplifier is to prepare short optical pulse strictly synchronized with the electron bunch. The amplifier is seeded by the laser pulse of 10 ps pulse duration and 30 kW peak power. The duration of the seeding pulse is much larger than the electron pulse time jitter of ± 1 ps, so it can be easily synchronized with the electron bunch. After the first stage the electron and the light beam are separated. The electron beam is guided through a nonisochronous bypass and the radiation enters the optical pulse shaping system. Details of the first stage FEL amplifier and the optical pulse shaping system are presented in [9]

The required level of the energy spread in the second FEL amplifier is induced only in the nonlinear stage of the FEL amplifier operation when the electrons be-

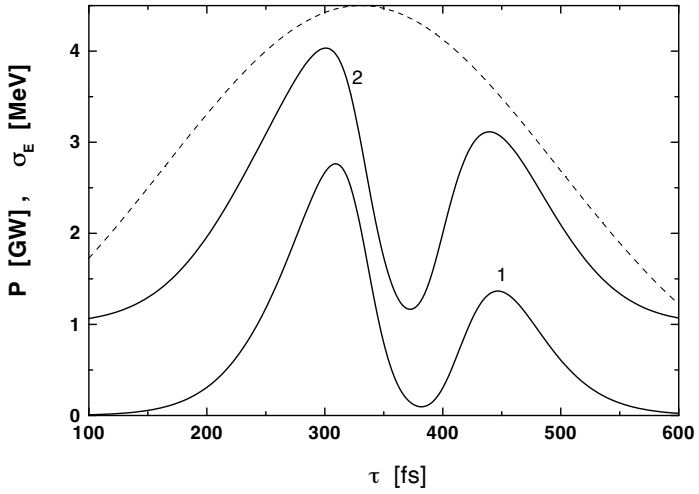

Fig. 4. Temporal profile of the output radiation (curve 1) and energy spread in the electron bunch (curve 2) at the exit of 523 nm FEL. Dashed line denotes current profile of the electron bunch.

come to lose visible fraction of their energy. In order to reach nonlinear stage, the undulator should be sufficiently long. Optimized length of the undulator is equal to 8.3 m, i.e. 110 undulator periods. Slippage effect at this distance play visible role in formation of the radiation, despite kinematic slippage (of about 60 microns) is visibly suppressed, by a factor of four, due to decrease of the group velocity of the radiation interacting with the electron beam [8]. This effect explains significant difference between the shape of the seeding pulse (see Figs. 3 and 4) and radiation profile and induced energy spread in the electron beam at the undulator exit.

A dispersion section is installed at the exit of the second stage of 523 nm FEL amplifier in order to provide more homogeneous distribution of the electrons in the phase at the entrance to the X-ray undulator. A simple chicane consisting of three dipoles with $R_{56} = 0.5$ mm is sufficient for this purpose.

X-ray undulator follows immediately after the second stage of the two-stage 523 nm FEL amplifier (see Fig. 2). Parameters of the femtosecond X-ray FEL amplifier are presented in Table 1. The only difference in parameters from the main option of the TTF FEL [2] is that the FWHM pulse duration is reduced down to the value of 30 fs. Figure 5 represents temporal structure of the radiation pulse at the exit of the X-ray FEL at the undulator length 26 m. Optimization of the parameters of the femtosecond foft X-ray facility at TTF has been performed with 3-D, time-dependent FEL simulation code FAST [7].

The electron bypass has to deflect the electron beam out of the straight flight pass to make room for the optical elements. In addition the microbunching introduced in the electron bunch in the first undulator has to be removed without increasing the overall length of the bunch significantly. The electron optical functions at the exit of 1st undulator and the entrance of the 2nd undulator are determined by the undulators and have to be matched by the bypass electron optics. The basic

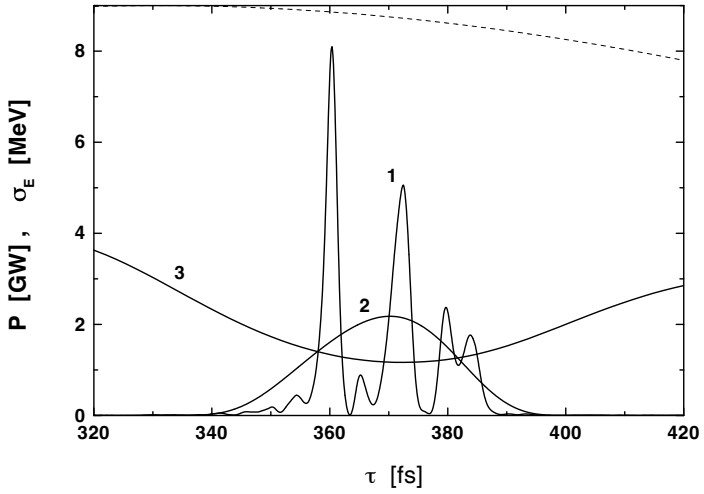

Fig. 5. Temporal structure of the output radiation from femtosecond X-ray FEL. Curve 1 corresponds to the single shot, and curve 2 is the averaged value. Curve 3 represent the energy spread along the electron bunch at the undulator entrance. Dashed line denotes current profile of the electron bunch.

Table 1
Parameters of femtosecond X-ray FEL at the TESLA Test Facility at DESY

Undulator	
Type	Planar
Period	2.73 cm
Peak magnetic field	0.497 T
External β-function	300 cm
Length of undulator	26 m
Radiation	
Wavelength	6.4 nm
Bandwidth, $\Delta\lambda/\lambda$	0.5%
rms angular divergence	15 μrad
rms spot size at the undulator exit	90 μm
Pulse duration (FWHM)	30 fs
Power average over pulse	2 GW
Flash energy	50 μJ
Average power	4 W
Peak spectral brilliance	3×10^{30} Phot./(sec$\times$ mrad$^2\times$mm$^2\times$ 0.1 % bandw.)

elements of the adopted symmetric bypass design are four dipole magnets. The first is located 1.3 m behind the first stage of 523 nm FEL amplifier and deflects the beam back in the direction parallel to the straight beam path at the distance of about 24 cm, which is sufficient for the installation of the optical elements. The total elongation of the electron beam path is approximately 12 mm. The layout of the bypass is shown in Fig. 6. In the middle of the bypass one finds a second mini-bypass, which serves for tuning the electron path length by up to 0.5 mm, i.e.

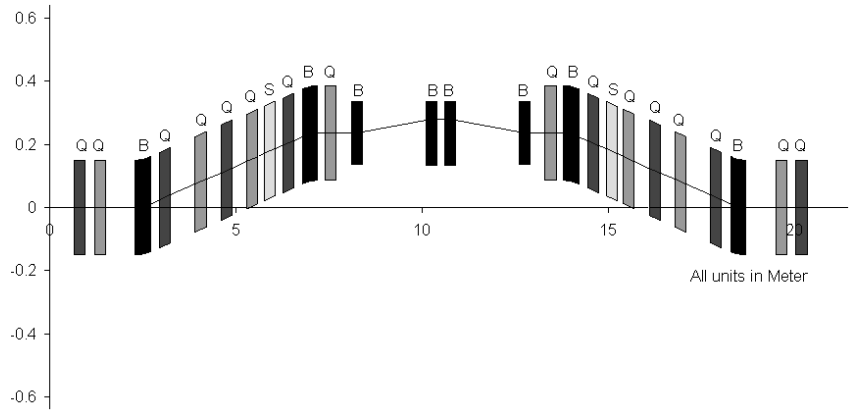

Fig. 6. Layout of the electron bypass. Here letters Q, S and B denote quadrupole, sextupole, and bending magnet, respectively.

Table 2
Parameters of the electron bypass

Main bypass	
Length	21 m
Extra path length	12.4 mm
Max. distance to the straight path	23.6 cm
Dipole bending angle	52.4 mrad
Extra path length for electrons with 0.1% energy deviation	0.73 μm
Tuning bypass	
Length of tuning bypass	4.8 m
Tunability of path length	0-0.952 mm
Max. distance to large bypass	43.6 mm
Tuning dipole bending angle	21.8 mrad
Extra path length for electrons with 0.1% energy deviation	0-1.86 μm

approximately 10 times of the bunch length. The additional focusing and defocusing quadrupole magnets are needed to adopt the bypass electron optics to that in the undulator, for decoupling of the beampath elongation from the electron energy and for keeping the transverse beam cross section small enough. The bypass parameter list is presented in Table 2 The transverse dimensions of the dipole and quadrupole magnets have been chosen such that they jut out in the direction of the straight beampath by no more than 15 cm. Preliminary optimization gives the length of the dipole and quadrupole magnets to be 20 cm and 30 cm, respectively. The final dimensions depend on the design of vacuum system.

For very short bunches, coherent synchrotron radiation (CSR) can dilute the horizontal emittance by similarly generated energy spread in the dipoles. Calculations of the CSR induced emittance dilution have been made using the DESY TRAFIC4 code [10] which includes field transients, bend-to-bend radiation, and radial forces. These results shows that the dilution of the slice emittance in the

bypass is about 10% .

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

[3] L. Lehr et al., Science 284(1999)635

[4] R. Tatchyn et al., Nucl. Instrum. and Methods A 375(1996)274

[5] J. Andruszkow et al., Phys. Rev. Lett. 85(2000)3825

[6] B. Faatz et al., DESY-print 00-94(2000)

[7] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Nucl. Instrum. and Methods A 429(1999)233

[8] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "The Physics of Free Electron Laser" (Springer, Berlin, 1999)

[9] W. Brefeld et al., DESY Print TESLA-FEL 2001-02, Hamburg 2001

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