STEPS TOWARDS X-RAY SOURCES BASED ON LINAC-DRIVEN FREE-ELECTRON LASERS

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Abstract

X-rays play a crucial role in the study of structural and electronic properties of matter on an atomic scale. With high-brilliance x-ray sources high resolution imaging and the observation of very fast chemical processes become possible. A high-brilliance x-ray free-electron laser (FEL) based on linear accelerator technology using the principle of self-amplified spontaneous emission (SASE) appears to be the most promising approach. However, the high electron beam quality required by the SASE FEL process presents challenges to the linear accelerator community. Recent results obtained in several SASE FEL test facilities in the visible and ultra-violet ranges have demonstrated the viability of injector systems to deliver high brightness electron bunches and longitudinal compression schemes to obtain a few kA peak current while preserving beam brightness over a small slice of the bunch length. Challenges to new facilities reside in understanding the underlying physics to extend the technology to the x-ray region (about 0.1 nm) and in developing high-resolution phase space diagnostics. After a brief introduction to the SASE principle, we review the encouraging results of the recent experiments and present technical concepts to meet the requirements in the FEL facilities presently under construction.

INTRODUCTION

There is a large interest in both the particle accelerator community and the synchrotron radiation users community to construct FELs operating in the x-ray region (about 1 Å). A list of x-ray FEL facilities presently planned is given in Table 1. The scientific applications of x-ray FEL radiation are discussed in extensive detail in [1, 2, 3, 4].

Location	**Facility**	**range [Å]**	Referen.
DESY	TESLA X-FEL	0.85-64	[1]
SLAC	LCLS	1.5-15	[5]
MIT-Bates	X-ray FEL	3-1000	[6, 7]
FERMI	ELETTRA	12-15	[8]
BESSY	SASE-FEL	12-600	[3]
INFN Rome	SPARX	15-135	[9, 10]
Spring-8	SCSS	36	[11]
Daresbury	4GLS	124	[12, 4]

Table 1: Proposed/planned x-ray FEL facilities (ordered by minimum wavelength reach).

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X-ray FELs will deliver photon beams with a peak brilliance nearly ten order of magnitude larger than present x-ray sources. These FELs are driven by linear accelerators producing short bunches (in the order of 0.1 ps) with normalized transverse emittances of about 1 mm·mrad. High density electron bunches are accelerated to energies between 10 and 20 GeV and travel through undulator magnets with a length of about 100 m. A large part of the increase in photon brilliance with respect to present x-ray sources is due to the contribution of the undulator spontaneous radiation alone, since the peak current inside the bunch is large and the undulator is relatively long. The spontaneous synchrotron radiation emitted by the bunch in the first meters of the undulator is amplified under the principle of Self-Amplified Spontaneous Emission (SASE) [13, 14]. After a sufficient length, the radiation power saturates on a level about 5 to 6 orders of magnitude higher than spontaneous radiation.

This type of x-ray source presents also the property of being easily tunable. The radiation wavelength λ_r of the first harmonic of the FEL radiation [15] is related to the period length λ_u of a planar undulator by

$$\lambda_\mathrm{r} = \frac{\lambda_\mathrm{u}}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \tag{1}$$

where $\gamma = E/m_\mathrm{e}c^2$ is the relativistic factor of the electrons, $K = eB_\mathrm{u}\lambda_\mathrm{u}/2\pi m_\mathrm{e}c$ the 'undulator parameter' and B_u the peak magnetic field in the undulator. Thus, the FEL wavelength is tunable either by changing the electron energy in the linac or by changing the gap height of the undulator (and thus its magnetic field).

Another characteristic of the SASE FELs is the extreme short radiation pulse. In order to reach peak currents of a few keV, the bunches have to be compressed down to sub-picosecond lengths. The length of the radiation pulse generated by these short bunches is in the order of 0.1 ps, which allows the study of very fast chemical and physical processes.

The feasibility of SASE FELs have been proved at infrared, visible and ultraviolet wavelengths. Proof-of-principle experiments on SASE FEL have been successfully conducted in various laboratories. FEL saturation has been observed with 385 nm in LEUTL at ANL [16], with 840 nm in VISA at UCLA [17] and with 98 nm in TTF1 at DESY [18, 19]. Moreover, first user experiments at VUV wavelengths have been conducted [20, 21] at the TTF1 FEL.

ELECTRON BEAM REQUIREMENTS

In a SASE FEL, lasing occurs in a single pass of a relativistic, high quality electron bunch through a long undulator magnet. The radiation power $P(z)$ grows exponentially with the distance z along the undulator

$$P(z) = P_\mathrm{o} \cdot A \cdot \exp\left(\frac{2z}{L_\mathrm{g}}\right)$$

where L_g is the field gain length, P_o the effective input power[1], and $A = 1/9$ in one-dimensional FEL theory with an ideal electron beam. This "high gain mode" requires an electron beam with transverse emittances of roughly

$$\epsilon_N \leq \gamma \frac{\lambda_r}{4\pi}$$

where ϵ_N is the normalized rms emittance and γ is the Lorentz relativistic factor of the electron. For a photon wavelength of 1 Å and typical undulator parameters the required beam energy is between 10 GeV and 20 GeV. At these energies, the emittance required is about 1 mm·mrad both in horizontal and vertical planes. This requirement is to be fulfilled by at least part of the beam or, rather to say, by a slice of the bunch. The so-called 'slice emittance' is therefore the relevant parameter.

At the same time, the energy spread and current of this slice has to fulfill that

$$\frac{\sigma_E}{E} < \rho \quad ,$$

which is the FEL parameter given by

$$\rho \approx \frac{1}{4\pi}\left(\frac{\mu_o e}{2m_e c}\frac{K^2 \hat{I} \lambda_u^2}{\gamma^2 \beta \varepsilon_N}\right)^{1/3}$$

where μ_o is the permeability of vacuum, $\hat{I}$ is the peak electron current and β is the mean value of the beta function in the undulator. Additionally, ρ determines the FEL gain length

$$L_g \sim \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

(as given in the one-dimensional FEL theory). For SASE saturation, the undulator length must be roughly 20 times the gain length. Maintaining a reasonable length for the undulator poses a restriction on the minimum value for ρ and therefore for the energy spread and peak current. Typical design values for x-ray FELs are $\sigma_E/E \sim 0.05\%$, $\hat{I} \sim 4$ kA and about 100 m undulator length. A significant deviation from these parameters can cause a dramatic decrease on the FEL gain and reduce the FEL power at the exit of the undulator. An example of the degrading effect on the FEL gain due to an increase of the transverse emittance in LCLS is shown in Fig. 1.

[1] The spontaneous undulator radiation is used as an input signal to the downstream part.

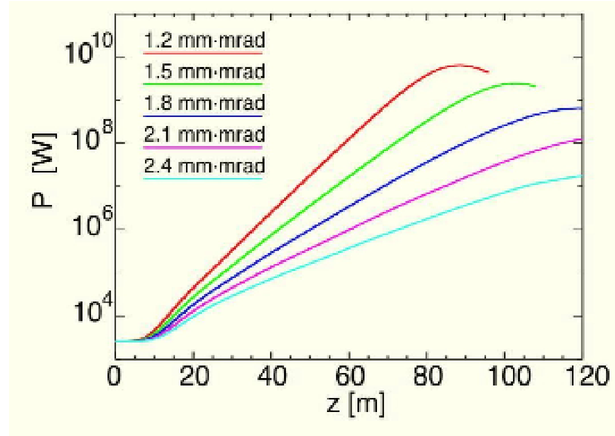

Figure 1: Development of the photon beam power as a function of the undulator length for various values of the transverse electron beam normalized emittance at LCLS. (Courtesy of S. Reiche)

The requirements on low emittance and high peak current electron beam are met with a high-brightness rf photocathode gun equipped with an emittance compensation solenoid, plus bunch length compression in stages at high energy, where space charge effects are reduced.

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 acceleration with minimal longitudinal and transverse emittance dilution.

Yet another requirement is the alignment of the electron beam trajectory in the undulator. The electron beam, focused in the undulator section to a transverse size of about 0.1 mm, has to be kept in essentially complete overlap with the photon beam during its passage through the undulator in order to maintain maximum amplification by intense electron-photon interactions. The straight trajectory inside the undulator can be achieved with beam-based alignment.

HIGH-BRIGHTNESS INJECTORS

RF photoinjectors have been developed as the most effective method of achieving very bright electron pulses. In a rf photocathode gun, electrons are emitted when a laser beam strikes the surface of the cathode. The cathode is placed at the middle plane of an rf cavity with very high accelerating field. The rf field boosts the electron bunch to relativistic energies in order to overcome the Coulomb forces that tend to blow up the emittance (so called space charge effect). As an example for rf gun, the side view of the LCLS design of a 1.6-cell S-band gun [22] is shown in Fig. 2.

The design goal of rf photocathode guns is a 3 ps-(rms)-long bunch of 1 nC charge with a normalized rms emittance of 1 mm·mrad. This corresponds to a peak current of about 100 A. These levels have not yet been simultaneously achieved to date, but most measurements reflect the

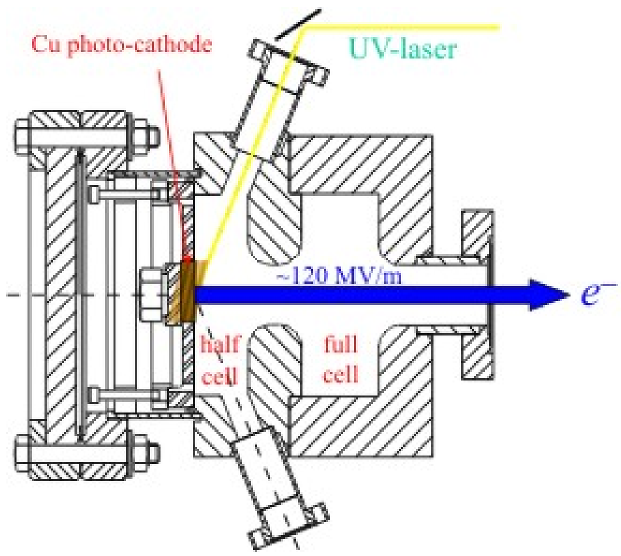

Figure 2: Side view of the RF photocathode design for LCLS

'projected' emittance. Some measurements have indicated sub-mm·mrad slice emittance levels [23, 24], but at a reduced charge of $0.1 - 0.3$ nC. A review of experimental results on high-brightness photoinjectors is given in [25]. A comparison of the brightness defined as

$$B = \frac{\hat{I}}{\varepsilon_N^2}$$

is shown in fig. 3.

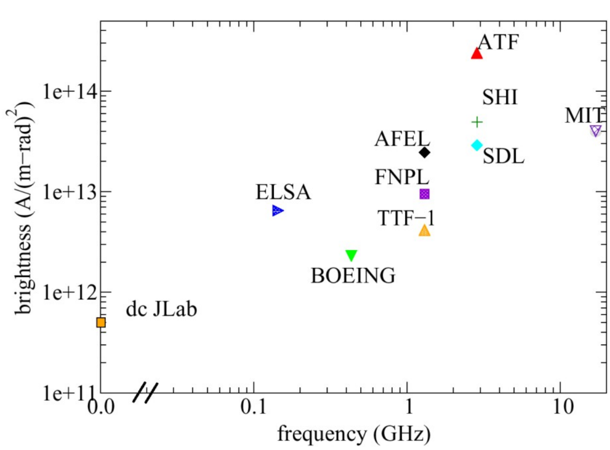

Figure 3: Comparison of the brightness of various photoinjectors (from ref. [25]).

LONGITUDINAL BUNCH COMPRESSION

The peak current produced by a low emittance gun is still not large enough in order to reach saturation within a reasonable undulator length. The bunch can be longitudinally compressed only at ultra-relativistic beam energies, where the space charge forces are reduced drastically.

Bunch compression is typically achieved by accelerating the bunch off-crest and using a magnetic chicane. The off-crest acceleration provides an energy chirp along the bunch length, so that the electrons in the head of the bunch gain less energy than the electrons in the tail. The magnetic chicane (for example, a series of four dipole magnets) introduces an energy dependent path length (see Fig. 4) so that the chirped bunch is compressed in length.

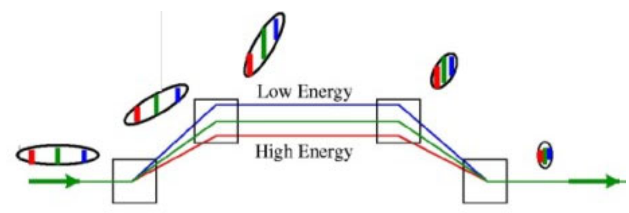

Figure 4: Schematic of a magnetic chicane for bunch compression.

The off-crest acceleration introduces, however, a non-linear energy correlation along the bunch train. For large incoming bunches the effect is non-negligible and can lead to the formation of a large spike at the head of the bunch as it is shown in Fig. 5. It is possible to compensate the non-linearities by including a higher harmonic rf accelerating section. This has been proposed for the first compressor in TESLA [27], in LCLS [28] in TTF2 FEL [29] and at Boeing [30].

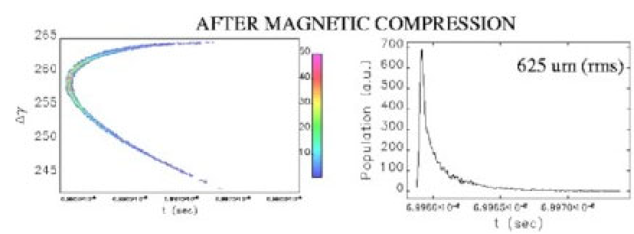

Figure 5: Simulation results of longitudinal compression of a long bunch including the non-linearities of the rf curvature. Longitudinal phase-space diagram (left plot) and profile (right plot) of the bunch after magnetic compression.

The off-crest acceleration in the linac can introduce timing jitter. The energy-phase correlation increases the sensitivity of the energy stability and the final bunch length to the phase jitter in the photocathode laser and rf timing. Energy jitter further increases the timing jitter due to the path length dependence of the magnetic chicane.

At very short bunch lengths, the Coherent Synchrotron Radiation (CSR) plays an relevant role in the beam dynamics inside the bunch compressor dipoles. The power dissipated increases with the square of the number of electrons and is, therefore, several orders of magnitude larger than the incoherent radiation (see Fig. 6). CSR effects in bunch compressors can have a tremendous impact on the beam (see for example [26]). Radiation from the tail of the electron bunch can catch up to the head of the electron bunch due to the curved electron path. This radiation field interacts with the bunch while traveling through the bending magnet, potentially adding correlated energy spread and emittance to the electron bunch. The effect of CSR maybe shielded by choosing a small enough vacuum chamber height. CSR effects have been extensively studied in simulations and taken into account in the design of magnetic chicanes.

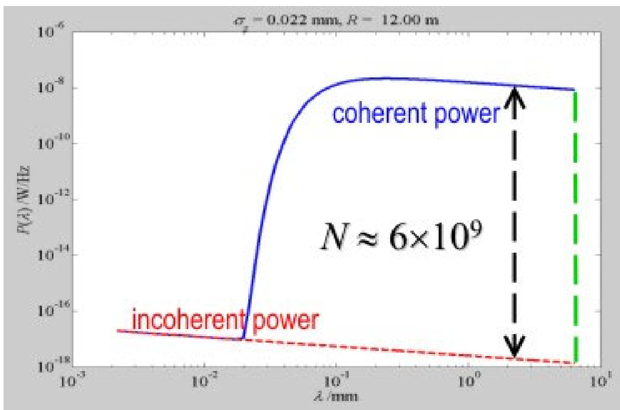

Figure 6: Radiation power spectra of the coherent and incoherent synchrotron radiation. The green dashed line indicates the cutoff of the vacuum chamber dimensions.

Due to all these phenomena described above, it is preferable to utilize two or three rather than one chicane and to compress in a multi-stage regime. A multi-stage bunch compressor presents the advantage of tuning the length of the FEL pulse. This ability of changing the radiation pulse length has been demonstrated at TTF1 [19]. Indirect measurements of the radiation pulse length (see Fig. 7) indicate the possibility to vary the width of the current spike between 30 fs and 100 fs by changing the compressor settings.

DIAGNOSTICS

A very important aspect for the operation of SASE FELs is electron beam diagnostics. Various techniques have been developed for the measurement of bunch lengths smaller than 1 mm, and for the measurement of the slice emittance and energy spread of compressed bunches.

A method streaking the bunch by a transverse mode rf structure has been successfully tested in SLAC [31]. The rf field deflects the bunch vertically and the beam is intercepted on a screen downstream the structure. The rf-phase is tuned so that the head and the tail of the bunch receive a different kick amplitude. Thus, the vertical profile of the spot at the screen corresponds to the longitudinal profile of the bunch. Scanning the strength of a quadrupole allows a measurement of the vertical slice emittance along the bunch length.

Several other methods to measure the bunch length have been investigated. The longitudinal bunch profile at TTF1

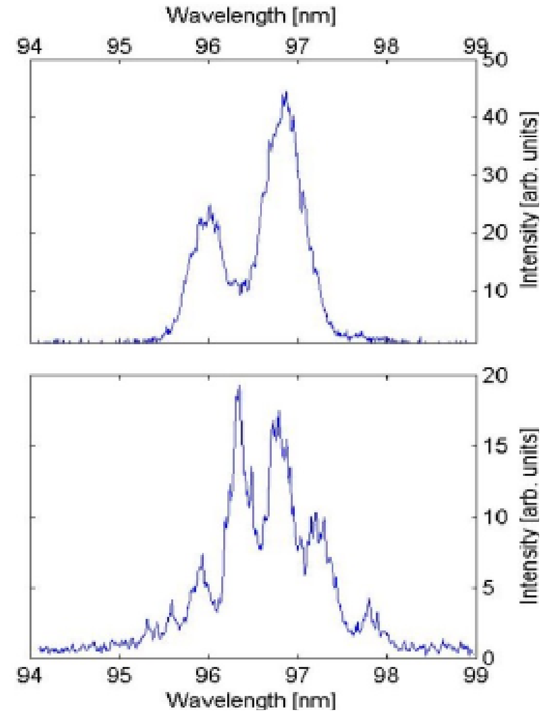

Figure 7: Spectra from ~ 40 fs (top) and ~ 100 fs(bottom) long FEL pulses. The number of longitudinal optical modes (spikes in the spectrum) depends on the electron bunch length.

has been measured using interferometry of coherent synchrotron radiation, longitudinal phase-space tomography [32] and by the means of a 300-fs-resolution streak camera looking at dipole synchrotron radiation [33]. Electro-optical sampling of the near field [34] and spectroscopy of coherent infrared radiation are planned for TTF2.

The diagnotic block placed between undulator modules requires a very compact design. Quadrupoles are placed on movable support and precise beam position monitors allows for beam-based alignment. A three dimensional picture of the diagnostic block (including wirescanners) mounted on a stable support for the TTF2 undulator section is shown in Fig. 8.

CONCLUSIONS

X-ray FELs will have between 8 to 10 orders of magnitude larger brilliance than present x-ray sources. Proof-of-principle experiments have demonstrated the capability of injectors and linac to deliver high quality electron beam that meet the requirements for FELs down to 80 nm wavelengths producing results in full agreement with theory. Although a gap of a factor 1000 in wavelength remains to be covered, a improvement on key electron beam parameters of a factor 2-3 is needed and is expected to be achieved. In the near future, TTF2 at DESY will test the feasibility for wavelengths down to 60 Å and will be the test-bed of a broad range of user experiments.

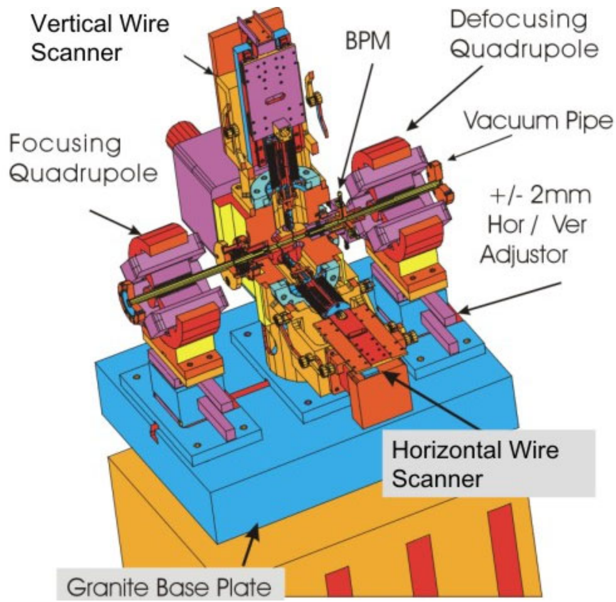

Figure 8: Diagnostic block and quadrupoles located between 4.5 m long undulator modules in TTF2.

REFERENCES

[1] R. Brinkmann, K. Flöttmann, J. Rossbach, P. Schmüser, N. Walker and H. Weise (eds.); "TESLA Technical Design Report, Part V The x-ray free-electron laser", DESY 2001-011, Hamburg, 2001.

[2] "LCLS The first experiments", http://www-ssrl.slac.stanford.edu/LCLS/papers/LCLS_Experiments_2.pdf

[3] "Visions of Science: The BESSY SASE-FEL"; *http://www.bessy.de/lab_profile/01.FEL/sc*

[4] 4GLS homepage *http://www.4gls.ac.uk*

[5] "LCLS CDR", SLAC-R-593, April 2002.

[6] "X-ray Laser User Facility at Bates Laboratory"; Proposal to the National Science Foundation, April 2003. *http://mitbates.mit.edu/xfel/fel_files/nsfproposal.pdf*

[7] T. Zwart et al., "The MIT Bates X-Ray Laser Project"; Proceedings of PAC'03, Portland (OR), May 2003.

[8] M. Altarelli, "The FERMI@ELETTRA Project"; *http://www.elettra.trieste.it/science/elettranews/volume44/en103.html*

[9] L. Palumbo, "Design Study of a Soft X-Rays SASE-FEL Source"; Proceedings of EPAC'02, Paris, June 2002.

[10] D. Alesini et al., "The SPARC Project: A High-Brightness Electron Beam Source at LNF to Drive a SASE-FEL Experiment"; Proceedings of FEL'02, Argonne (IL), Sept. 2002.

[11] SCSS homepage *http://www-xfel.spring8.or.jp/SCSS.htm*

[12] D.T. Clarke et al., "4GLS - A Fourth Generation Light Source that for the biomedical scientist is more than a laser and more than a storage ring"; SPIE Preprint, Feb. 2002.

[13] R. Bonifacio, C. Pellegrini, L.M. Narducci, Opt. Commun. **50,** 373 (1984)

[14] A.M. Kondratenko, E.L. Saldin, Part. Accelerators **10,** 207 (1980)

[15] J.M.J. Madey, J. Appl. Phys. **42,** 1906 (1971).

[16] S. Milton et al., "Exponential gain and saturation of a self-amplified spontaneous emission free-electron laser"; Science **292**, 2037 (2001).

[17] A. Tremaine et al., "Saturation measurements of a visible SASE FEL"; Proceedings of the PAC'01, Chicago (IL), May 2001.

[18] V. Ayvazyan et al., "Generation of GW Radiation Pulses from a VUV Free-Electron Laser Operating in the Femtosecond Regime"; Phys.Rev.Lett.**88**, 104802 (2002).

[19] V. Ayvazyan et al., "A new powerful source for coherent VUV radiation: Demonstration of exponential growth and saturation a the TTF free-electron laser"; Eur.Phys.J.D **20**, pp 149-156 (2003).

[20] H. Wabnitz et al., "Multiple ionization of atom clusters by intense soft X-rays from a free-electron laser"; Nature Vol. 420, pp 482-485, Dec.2002.

[21] L. Juha et al., "Ablation of various materials with intense XUV radiation"; Proc. of FEL'02, Argonne (IL), Sept. 2002.

[22] C. Limborg et al., "New optimization for the LCLS photo-injector", Proceedings of the EPAC'02, Paris, June 2002.

[23] W. Graves et al., "Experimental study of sub-ps slice electron beam parameters in a photoinjector"; submitted to FEL-2002, Argonne (IL), Sept. 2002.

[24] D.H. Dowell et al., "Slice emittance measurements at the SLAC gun test facility"; submitted to FEL-2002, Argonne (IL), Sept. 2002.

[25] P. Piot, "Review of experimental results on high-brightness photo-emission electron sources"; Submitted to World Scientific, DESY M 02-02, Dec. 2002.

[26] M. Hüning, Ph. Piot, H. Schlarb, "Observation of longitudinal phase space fragmentation at the TESLA test facility free-electron laser"; NIM A **475** Issues 1-2, pp 348-352, Dec. 2001.

[27] M. Ferrario et al., "Conceptual design of the XFEL photoinjector"; TESLA-FEL-2001-03, Feb. 2001.

[28] P. Emma, "X-band rf harmonic compensation for linear bunch compression in the LCLS"; LCLS-TN-01-1, Nov. 2001.

[29] K. Flöttmann, T. Limberg, P. Piot, "Generation of ultrashort electron bunches by cancellation of nonlinear distortions in the longitudinal phase space"; TESLA-FEL-2001-06, June 2001.

[30] D. Dowell et al., "Magnetic pulse compression using a third-order linearizer"; Proc. of PAC'95, Dallas (TX), May 1995.

[31] P. Krejcik et al., "A transverse rf deflecting structure for bunch length and phase space diagnostics"; Proc. of PAC'01, Chicago (IL), May 2001.

[32] M. Hüning, "Investigations of the longitudinal charge distribution in very short electron bunches"; Proc. of DIPAC'01, Grenoble, May 2001.

[33] Ch. Gerth et al., "Bunch length and phase stability measurements at the TESLA test facility"; Proc. of FEL'02, Argonne (IL), Sept. 2002.

[34] M. Brunken et al., "Electro-optic experiments at the TESLA test facility"; Proc. of FEL'01, Darmstadt, Sept. 2001.