TECHNOLOGY CHALLENGES TOWARDS SHORT-WAVELENGTH FELS

J. Rossbach, Universität Hamburg and DESY, 22603 Hamburg, Germany

Abstract

The paper sheds some light on achievements in accelerator technology that paved the way towards short-wavelength FELs, specifically the FLASH facility at DESY. Also, a few of the technical challenges are discussed which we are facing in view of future X-ray FELs.

INTRODUCTION

Free-electron lasers (FEL) operating in the SASE mode (self-amplified spontaneous emission) at wavelengths far below the visible are now with us since several years, and more, and even more ambitious, projects are ahead of us. Although most of the basic theory is known since the early eighties, it took more than twenty years until FEL saturation was demonstrated experimentally at wavelengths below the visible. Even more, it took almost 30 years until a user facility was put in operation in the VUV regime, although it was clear from the very beginning, that such a radiation source would open up an entirely new world of possibilities for experimenters.

The major reason for this long time span was related to the unprecedented electron beam quality needed to achieve saturation within a reasonable undulator length. Considerable R&D on accelerator physics and technology was indispensable to come to a credible and reliable design of a (soft) X-ray FEL. In particular, it was not only necessary to develop technologies for producing ultra-relativistic electron bunches with high charge (typically 1 nC), small normalized emittance (typically 1 mrad mm) small energy spread (order of 100 keV after compression) and very short bunch length (10 fs range, thus achieving both the kA peak current needed for the FEL and the short radiation pulses desired by users), but it was as important to invent novel beam diagnostics tools to verify and control the beam properties at a micrometer precision level – in all three dimensions. This broad scope of tasks could only be accomplished by big accelerator centres, being able to initiate and conduct a coordinated effort of the full spectrum of accelerator scientists and engineers. This broad spectrum of expertise was traditionally cultivated at big labs dedicated to high-energy particle physics (HEP), for their permanent demand of more powerful and more sophisticated accelerators. It is thus not by accident that the first X-ray FEL programs were initiated mainly by such labs like DESY and SLAC. It will be a most awarding science management task (and, in view of the more and more project oriented funding policies, a very challenging one) to keep alive and even extend the fruitful collaboration of accelerator scientists from both HEP and FEL communities.

The present paper is not considered a review article on this extremely broad subject. It is rather a personal review, mainly referring to the almost 14 years of R&D effort conducted at DESY, Germany towards the FLASH user facility. To a large extent, this effort was based on, and conducted by, the international TESLA collaboration, with the superconducting accelerator called "TESLA Test Facility" still being the backbone hardware. In the spirit mentioned above, part of the accelerator beam time is still allocated to HEP-related accelerator R&D towards the International Linear Collider (ILC), being based on the same TESLA superconducting accelerator technology.

The list of technology issues mentioned in the following is by far not complete. It represents a personal, partly arbitrary selection of topics that are FEL specific, where considerable progress has been made, but which should keep us busy for another while.

TRANSVERSE SPACE CHARGE

In linear 1D theory [1], the power e-folding length L_g of the high-gain FEL can be expressed by

$$L_g = \frac{1}{\sqrt{3}} \left[\frac{2m}{\pi\mu_0 e^2} \frac{\gamma^3 \lambda_u}{K^2 n_e} \right]^{1/3} \propto n_e^{-\frac{1}{3}} \tag{1},$$

where λ_u is the undulator period, K the undulator parameter, γ the electron energy in units of its rest energy, and n_e is the electron density in the lab frame. In order to achieve a sufficiently short power gain length L_g, there is little alternative to calling for very high charge density. Taking into account that particles with large betatron amplitudes fall out of FEL resonance, large n_e must be realized in a combination of small radial beam emittance ε_r and large peak current $\hat{I}$. Such an electron beam is subject to considerable space charge forces, even though such forces are largely suppressed at ultrarelativistic energies. The impact on transverse electron focusing can be estimated from the focal length f generated by the linear defocusing forces on a beam drifting along the accelerator over a distance z ($f > z$ assumed):

$$f \approx \frac{ec}{r_e} \frac{\overline{\beta}\varepsilon_{norm}}{z} \frac{\gamma^2}{\hat{I}} \tag{2}$$

With typical numbers for the normalized emittance $\varepsilon_{norm} = \beta\gamma\varepsilon_r \approx 1\,\mathrm{mrad\,mm}$, the average beta function $\overline{\beta} \approx 10\,\mathrm{m}$, the peak current $\hat{I} \approx 1\,\mathrm{kA}$, and the beam energy $\gamma \approx 200$, we get a focal length as small as $f \approx 10\,\mathrm{m}$ already after a few meters of passage length z.

FEL Prize and New Lasing

As a consequence, the electron beam carries its own focusing system, i.e. it is difficult to control the transverse beam size just by external quadrupole magnets. This is illustrated in Fig. 1, where the beta functions at FLASH are calculated for different assumptions on the peak current [2]. Note that the peak current inside the bunch is by far not constant (see below) such that different parts of the bunch acquire different focusing. It is then difficult to tell whether the lasing part of the beam has the desired focusing inside the undulator.
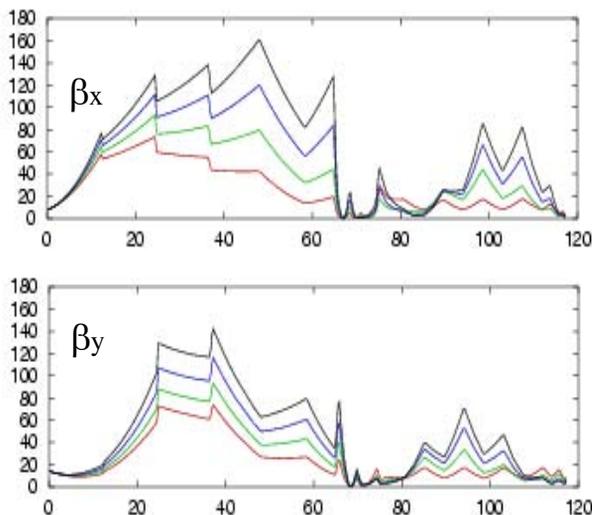
Figure 1: Optics beta functions at FLASH for the beamline after the final bunch compression at 380 MeV, calculated for different peak currents: $\hat{I}$ = 0 kA (red), 1 kA (green), 2 kA (blue), 3 kA (black). It is assumed here that space charge forces are negligible before the compression where the peak current is much lower.

Generation of low emittance electron beams

The reliable generation of electron beams with the desired small emittance is of outmost importance for the over-all design and for the performance of an X-ray FEL. In particular, the requirement that the emittance should fulfil (at least approximately) the condition $\varepsilon_r \leq \lambda_{Light}/4\pi$ is extremely demanding if radiation wavelengths (first harmonics) around $\lambda_{Light} \approx 1$ Angstrom are to be achieved. Generally this is the major reason for choosing a rather high electron beam energy beyond 10 GeV at LCLS and at the European XFEL. The electron source is thus the single component where improvements would have the largest impact on the overall design, performance and costs of an X-ray FEL. An overview of this subject is beyond the scope of this paper and can be found in Ref. [3].

At present, most of the FEL projects are based on a RF gun [4]. Through appropriate choice of cathode material and RF frequency, RF guns have been developed both for superconducting and normal conducting linacs, i.e.

serving for a wide range of duty cycles and bunch repetition rates. It is of particular importance, that very recently both R&D lines have reported success in achieving the design emittance of approx. 1.0 mrad mm (normalized) for 1 nC charge [5,6]. In order to reduce the nonlinear part of space charge forces, it is beneficial in these guns that the drive laser pulses are shaped towards flat transverse and longitudinal profiles.

It was pointed out before that the lower the beam emittance the better. It is thus exciting that there are alternative concepts potentially performing even better than RF guns:

- A thermionic gun based on a single crystal CeB_6 cathode is used at SCSS [7] and has already demonstrated promising results.
- An array of nanometer size field emitters immediately followed by a high voltage pulsed diode is under study at PSI in order to significantly reduce the thermal emittance and to suppress emittance growth due to space charge forces directly after the emission process [8].
- A dramatic progress might be achieved by plasma-based laser-wakefield acceleration on which a real break-through was demonstrated recently by demonstrating an electron beam of up to 1 GeV and only a few % momentum width [9] with a tabletop setup. Momentum spread, stability, and the transport of the beam into an FEL undulator remain critical issues.

Whatever the electron gun is, precise measurement of the emittance is very critical, in particular since the phase space distribution will be everything else but trivial. Thus, measurements of phase space distribution at resolution in the 10 μm range (in all three dimensions!) are desired. But even if the measurement is restricted to the longitudinal projection of the bunch, it is not trivial to find a parametrization of the distribution adequate for the FEL physics, the reason being that the phase space distributions are generally by far not Gaussian. The general approach is to describe the beam quality in terms of the rms-emittance $\varepsilon_x = \sqrt{\langle x \rangle^2 \langle x' \rangle^2 - \langle x \cdot x' \rangle^2}$. Fig. 2 illustrates a few phase space distributions measured at FLASH with almost the same rms emittances. The question remains whether all these distributions are really equivalent in terms of FEL performance, or whether more appropriate figures of merit should be developed.
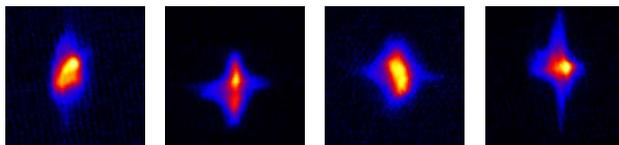
Figure 2: Various phase space distributions measure at FLASH. Are they all equivalent in terms of FEL performance?

SHORT BUNCH ISSUES

From FEL point of view

As mentioned before, in terms of emittance preservation a high peak current in the kA range is only tolerable at ultrarelativistic beam energies. As a consequence, the kA peak current is generated by magnetic bunch compression at some 200 MeV beam energy. In practice it is an unavoidable consequence that this leads to a very short bunch length in the 0.1 mm range. Very strong coherent fields are generated which have a large and detrimental effect on the beam dynamics. As an example, Figure 3 illustrates the longitudinal phase space distribution 1 m after the exit of the first bunch compressor of FLASH as predicted by numerical simulation. It is seen that the phase space distribution is distorted at the head of the bunch due to combined interaction of the electrons with space charge Coulomb forces and coherent synchrotron radiation (csr) generated in the bending magnets of the chicane. For details on beam dynamics simulation in presence of csr, see Ref. [10].

This interaction becomes even more pronounced during final compression. Figure 4 shows the calculated longitudinal phase space distribution in front of the undulator. csr effects are very pronounced in the head of the bunch, which is the only part of the bunch achieving high enough peak current as to expect FEL gain saturation.
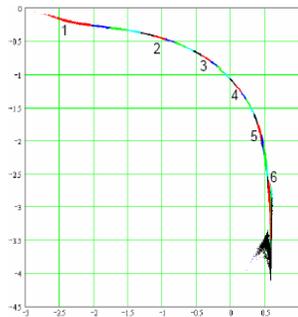
Figure 3: Longitudinal momentum distribution 1 m after the first bunch compressor of FLASH. The head of the bunch is to the right.
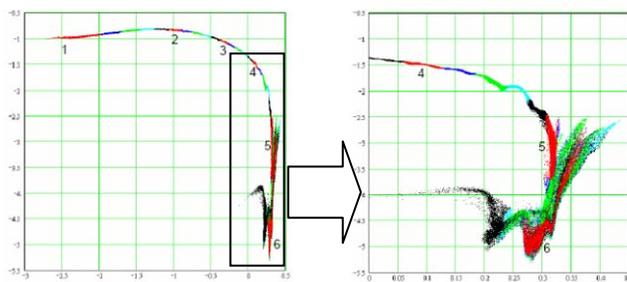
Figure 4: Longitudinal momentum distribution in front of the undulator. The plot on the r.h.s. shows the head of the bunch zoomed.

Csr effects do not only distort the momentum distribution but also the transverse phase space. As a consequence, not all the particles within the head of the bunch have an emittance sufficiently small for lasing. Figure 5 indicates the current distribution resulting from Figure 4 (colours representing the respective particles in Figure 4). The black curve indicates *that* fraction of the particles located within an emittance smaller than the tolerable one ($\varepsilon_{x,y}^{n} \leq 3 \cdot 10^{-6}\,\pi\mathrm{m}$). This part of the bunch achieves a peak current of 1400 A and is only approx. 60 fs (FWHM) long. According to FEL simulation [11], such a beam would generate a radiation pulse approx. 30 fs (FWHM) in length, which agrees nicely with the pulse length measured at FLASH.

Various techniques have been established at DESY to determine the longitudinal bunch current profile experimentally. One of the most powerful ones makes use of a transverse deflecting mode cavity resonator ("LOLA")[12,13]. LOLA's capability of resolving very detailed longitudinal features of the bunch is illustrated in Figure 6.
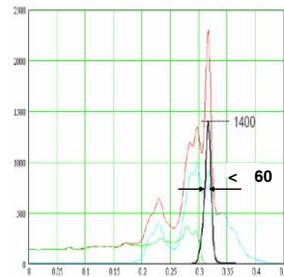
Figure 5: Predicted current distribution in front of the undulator according to beam dynamics calculations.
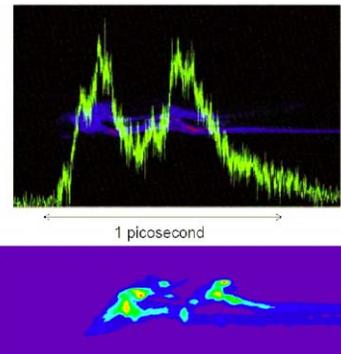
Figure 6: Longitudinal charge distribution within a single electron bunch of FLASH at DESY. Upper part: Image of the bunch on an observation screen, located downstream of the transverse mode cavity LOLA streaking the bunch transversely by a time dependent electro-magnetic field. The horizontal direction corresponds to the time. Only the part containing the spike at the head of the bunch is shown. The (green) solid curve shows the charge density profile projected onto the longitudinal position, i.e. the current profile. In this particular setting of bunch compression parameters, the spike is actually split into two parts approx. 300 fs apart, each part being shorter than 120 fs /(FWHM). The lower part of the figure shows the prediction of numerical beam dynamics simulation.

Due to the pronounced beam dynamics effects in the vicinity of the high peak current spike, not only the distribution of electron not only in the longitudinal, but also the transverse phase space can be heavily distorted. The transverse phase space distribution thus varies considerably along the internal bunch coordinate at FLASH, see Figs. 7,8 [14] illustrating that a capability of measuring properties of bunch slices is essential at an X-ray FEL.
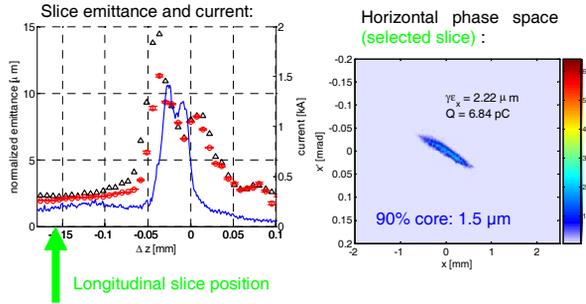
Figure 7: Horizontal phase space distribution of those electrons in the bunch located at the longitudinal position indicated by the green arrow, measured with LOLA at FLASH. Since this a position with relatively small current (blue solid line), the emittance is undistorted.
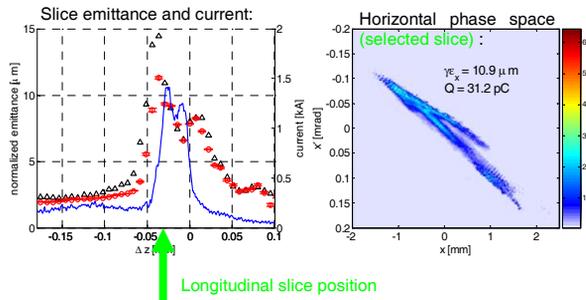
Figure 8: Same conditions as Fig. 7, but now a slice is sampled where the bunch current is high. The distribution of particles within this slice is heavily distorted.

In principle, we should know the bunch properties at a longitudinal resolution smaller than the cooperation length, i.e. for X-ray FELs in the sub-fs range. This is presently not accessible with time-domain beam diagnostics techniques. As an alternative, the coherent part of the infrared (IR) spectrum $dU/d\lambda$ radiated by the electron bunch when traversing magnetic fields or discontinuities like metallic foils contains information about the longitudinal structure function $F(\lambda)$ [15]:

$$\frac{dU}{d\lambda} = \left(\frac{dU}{d\lambda}\right)_1 \left(N + N(N-1)|F(\lambda)|^2\right) \qquad (3)$$

Here, $(dU/d\lambda)_1$ is the spectral density of a single electron, and N is the total number of electrons radiating. Such measurements should cover the spectral range down to 1 µm wavelength, and they should be, preferably, single shot measurements since some effects taking place at the micrometer-scale are likely to fluctuate considerable from bunch to bunch. As an example, Fig. 9

shows the single bunch spectrum at FLASH taken under SASE conditions. While a unique reconstruction of the longitudinal charge profile is hardly possible due to the loss of phase information, it is easy to identify evidence for substructure inside the bunch occurring at length scales well below the size of the lasing spike.

The coherent IR signal seems to be a good candidate for providing input signal for a SASE feedback loop. In principle, one might think that the maximum total IR power should be correlated with optimum compression and thus maximum SASE. It is, however, not so simple as seen from Fig. 10 [16]. While there is indeed a clear correlation between SASE and IR power within some range, maximum IR power is observed with only little SASE left, most like due to over-compression.

Achieving ultrashort bunches in a reliable way requires not only precise understanding of beam dynamics and lots of advanced diagnostics. In the first place, high stability of rf phase regulation in the 0.1° is needed which is very challenging ti achieve, see. Fig. 11.
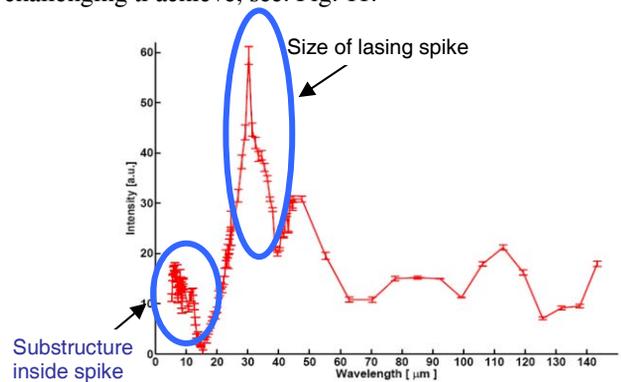
Figure 9: Single shot infrared spectrum taken at FLASH.
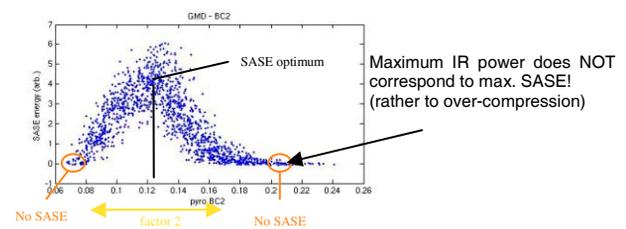
Figure 10: SASE power (vertical axis) versus total IR power measured at FLASH with a pyro detector [16].
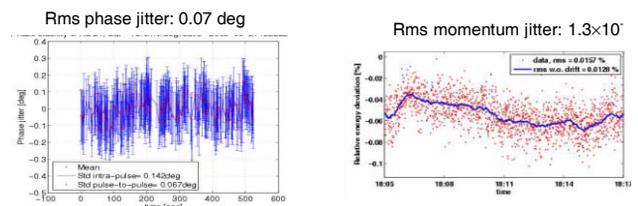
Figure 11: RF phase jitter and rms momentum jitter after first bunch compression at FLASH.

From FEL User point of view

What has been said so far results from requirements of the SASE process – almost independent of user needs. For many users, it is the capability of generating ultra-short, powerful X-ray pulses what makes FELs so attractive. They are thus interested in pulses as short as possible. The lower limit is obviously determined by the cooperation length l_c. At FLASH, with $l_c \approx 1.3\ \mu$m at 13 nm, this limit has been almost achieved with a pulse length $l_{pulse} \approx 3\ \mu$m , i.e. the radiation puls length is almost Fourier limited. At Angstrom FELs, l_c will be as short as $0.03\ \mu$m. This opens up the possibility to generate attosecond pulses [17,18], and calls for electron bunch diagnostics at sub-femtosecond resolution, both big challenges not yet met.

Synchronization Issues

The radiation pulses length being in the 20 fs range, it is important for users to have the pulses arriving at a time jitter well below 100 fs with respect to a reference clock that can be used for a pump-probe set-up. The underlying problem is that a state-of-the-art rf microwave oscillator represents an excellent master clock, but it is impossible to distribute rf signals by rf cables over long distances at fs stability. Techniques are under development to overcome this limitation [19-21], involving electro-optical detection of bunch arrival time, a stabilized optical fibre transmission line and an optical-only master clock system. Presently, a bunch–to-bunch time arrival stability of 200 fs rms has been verified [19, see Fig. 11. It is worth noting that the bunch arrival time is measured at ~10 fs resolution. With the help of an all-optical synchronization system it should become possible to stabilize many accelerator subsystems and lasers with respect to each other at <50 fs precision, even over distances some 1 km apart.
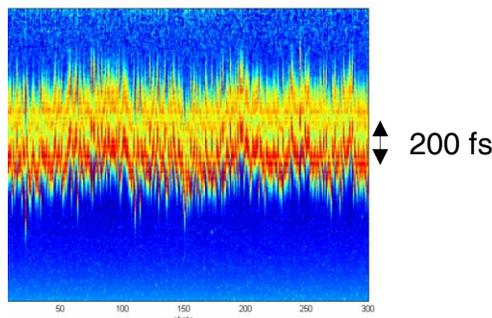
Figure 11: Fluctuation of bunch arrival time of 300 consecutive, compressed bunches at FLASH, measured by electro-optic modulation [19].

CONCLUSION

Impressive progress in accelerator technology made over the past 10-20 year was the backbone of the successful implementation of FELs in the VUV-and soft X-ray regime. Still it is not yet possible to measure the electron beam properties at the undulator entrance at such precision and resolution that the FEL radiation could be inferred from this information at sufficient precision. In particular in view of X-ray FELs being under way, there is thus good reason to support even more refined beam dynamics investigations as well as precise beam diagnostics with micrometer and femtosecond resolution.

ACKNOWLEDGEMENT

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