# ACCELERATOR LAYOUT AND PHYSICS OF X-RAY FREE-ELECTRON LASERS

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## *Abstract*

X-ray Free-Electron Lasers facilities are planned or are already under construction around the world. This talk covers the X-Ray Free-Electron Lasers LCLS (SLAC), European XFEL (DESY) and SCSS (Spring8). All aim for self-amplified spontaneous emission (SASE) FEL radiation of approx. 0.1 nm wavelengths. The required excellent electron beam qualities pose challenges to the accelerator physicists. Space charge forces, coherent synchrotron radiation and wakefields can deteriorate the beam quality. The accelerator physics and technological challenges behind each of the projects will be reviewed, covering the critical components low-emittance electron gun, bunch-compressors, accelerating structures and undulator systems.

## INTRODUCTION

X-rays have played for many decades a crucial role in the study of structural and electronic properties of matter on an atomic scale. Free electron laser X-ray sources can provide ultra-high brilliant and sub-100fs pulse length coherent radiation. This will allow the research in this field to enter a new era. Linear accelerator driven FELs using the principle of self-amplified spontaneous emission (SASE) [1] appear to be the most promising approach to produce this radiation in the Å wavelength regime. Approaching this short wavelength requires large beam energies and thus rather huge linear accelerator installations. Consequently, only three projects are proposed so far which aim for shortest radiation wavelength.

The first facility of this type, using part of the existing SLAC linac, is under construction here at Stanford and will become operational in 2009 [2].

The XFEL was originally proposed as integral part of the TESLA project together with a 500 – 800 GeV e+e- Linear Collider based on superconducting RF (SRF) technology [3]. In 2003 the German government decided to approve the XFEL as an European project located at DESY in Hamburg. Construction is expected to start in 2006 with first beam in 2012.

The SCSS is proposed at SPRING8 in Japan with the aim to start operation in 2010. This layout relies on C-Band acceleration technology developed for the Japanese Linear Collider (JLC) [4].

In addition to this large scale facilities their exist proposals for FELs reaching the soft X-ray/VUV regime. These projects have lower electron energies and reach the X-ray regime by higher order FEL processes like **H**igh **G**ain **H**armonic **G**eneration (HGHG). An overview of the present FEL projects is given in [5].

## *ELECTRON BEAM REQUIREMENTS*

The electron beam quality and stability required by the SASE process presents considerable challenges to the linear accelerator community. The following basic scaling laws for a Self-Amplified Spontaneous Emission FEL drive the layout of all facilities:

$$\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}, \tag{1}$$

with $\varepsilon_N$ the normalized emittance, $\lambda_r$ the FEL resonant wavelength and $\gamma$ the relativistic factor. The resonance condition is written as:

$$\lambda_r = \frac{\lambda_u (1+K^2)}{2\gamma^2} \tag{2}$$

with $K = 93.4\lambda_u B_{RMS}$ being the undulator parameter ($B_{RMS}$ the RMS undulator field, $\lambda_u$ the undulator period length). The gain length $L_g$ is given by

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

with the FEL parameter $\rho$

$$\rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{PK}}{I_A}\frac{\lambda_u}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{\frac{1}{3}}, \tag{4}$$

where $I_{PK}$ is the peak current, $I_A \approx 17\text{kA}$ and $\beta$ the average beta-function in the undulator.

Finally the energy spread has to be smaller than the FEL parameter

$$\frac{\sigma_E}{E} < \rho. \tag{5}$$

The gain length is underestimated in this 1d-model, and saturation is usually reached after 10−20 gain length. To keep the gain length short means increasing the peak current while decreasing the normalized emittance. Optimized FEL parameters call thus for peak currents of 2-5 kA and a normalized emittance of around 1 mm mrad.

An important feature of X-Ray FELs is the fact that the stringent electron beam parameters have to be reached for a 'slice' of the bunch only. The slippage length, i.e. the difference between the electron and photon path length equals one radiation wavelength per undulator period, or approx. $0.5\ \mu\text{m}$ ($\approx 1.7$ fs) along a typical XFEL undulator. Many of the collective effects deteriorate mainly the 'global' bunch properties, while leaving the slice parameters unaffected.

SASE test facilities in the visible and vacuum-ultra-violet wavelength range were built and operated during the last years. The results have demonstrated the viability of the challenging accelerator subsystems and the good understanding of the SASE process in this wavelength regime.

## OVERALL LAYOUT

### *XFEL*

The layout of the XFEL is sketched in Figure 2. It is laid out as a multi-user facility. In its first stage, it will have 5 undulator beamlines, 3 of which are SASE-FELs (two for the Å wavelength regime, one for softer X-rays), the other two for hard X-ray spontaneous radiation. The site allows extending the user facility for more beam lines in a later stage.

The undulator sections have a maximum total length of 250 m. Variable gap 5 m long undulator segments are foreseen, which not only permits to independently adjust the photon energy within certain limits, but also facilitates the precise steering of the electron beam for optimum overlap with the photon beam.

The undulator parameters have been optimized for one Å wavelength at beam energy of 17.5 GeV. This implies that at the nominal maximum beam energy from the linac of 20 GeV at 23MV/m accelerating gradient, the $^{57}$Fe line at 0.8 Å, of interest for certain experiments, will be accessible. Furthermore, the expected higher performance of the superconducting cavities (see below) will permit to operate at even shorter wavelength, provided that the electron beam quality can also be further improved to guarantee saturation in the SASE FEL process.

The site for the XFEL has the linac starting on the DESY site, permitting to make optimum use of existing infrastructure, and the user facility in a rural area about 3km west-northwest from DESY (see Figure 1). The legal procedure to obtain permission for construction is expected to be completed by end of 2005. The project organization at the European level is ongoing with the goal to prepare the documents required for the technical definition and organizational structure of the project by 2005. The final decision to move into the construction phase is expected for 2006. The construction time until beam operation will be 6 years. The total project cost is estimated at 684 M€ (year 2000 price level).

Figure 1: Site for the XFEL starting at DESY and extending approx. 3.3 km to the North-West.

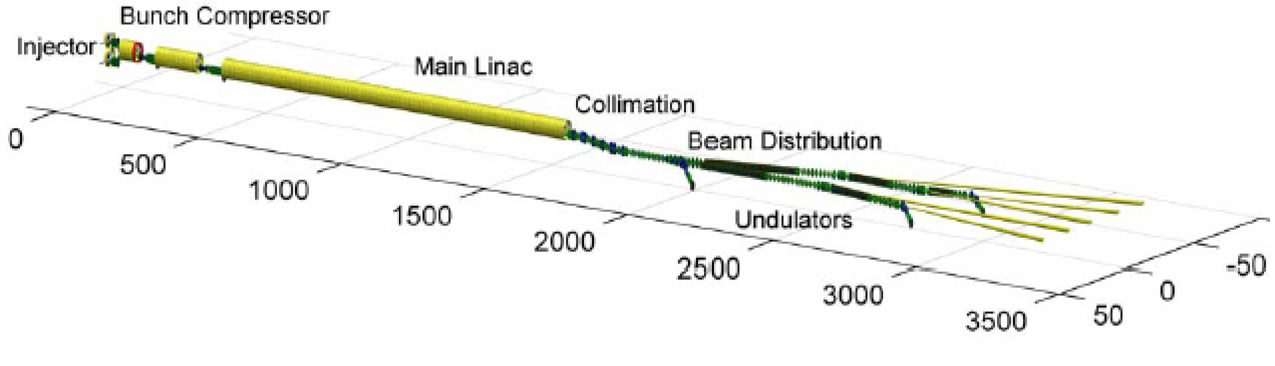

Figure 2: Layout of the XFEL

### *LCLS*

The LCLS makes use of the last third of the SLAC linac. One fixed gap, 112 m long undulator is foreseen for the initial phase, with an extension to more undulator beamlines being straight forward. The undulator parameters are optimized for 1.5 Å wavelength at a beam energy of 15 GeV.

Undulator system procurement is underway, with the complete delivery of the undulator system in 2007. The LCLS construction will start in 2006, FEL commissioning is planned in 2008 and operation is then foreseen for 2009. The project budget amounts to 379 M$.

### *SCSS*

The SCSS site is located in parallel to the long SPRING8 beamline. A total length of approx. 1 km is available on the SPRING8 site, which drives the layout towards a high gradient linac and small gap undulator. A 250 MeV test facility is being constructed to test the crucial components (therminoic gun, buncher, C-band acceleration, bunch compression and in-vacuum undulator) starting end of 2005. With input form this test facility construction of the SCSS can start in 2006 with FEL commissioning planned for 2010-11[6].

An overview of the main X-ray FEL parameters is given in Table 1.

Table 1: Selected Parameters of X-ray FELs

| | LCLS | XFEL | SCSS |
|---|---|---|---|
| Radiation Properties | | | |
| Wavelength [nm] | 0.15 | 0.08-6.4 | 0.1 |
| Sat. length [m] | 87 | 140 | 80 |
| # of Undulators | 1 | 5 (10) | 1 |
| Electron Beam Properties | | | |
| Energy [GeV] | 15 | 6-20 | 6-8 |
| Bunch Charge [nC] | 0.2 – 1 | 1 | 0.4 |
| Bunch Length [µm] | 8-22 | 25 | 25 |
| Energy Spread | 1e-4 | 1.5e-4 | 1.5e-4 |
| Emittance [mm mrad] | 0.85-1.2 | 1.4 | 0.85 |
| Peak Current [kA] | 2.1-3.4 | 5 | 3 |
| Main Linac Parameters | | | |
| RF Frequency [GHz] | 2.85<br>S-Band | 1.3<br>L-Band | 5.71<br>C-Band |
| Gradient [MV/m] | 20 | 23 | 35 |
| Linac Length [m] | 0.9 | 1.5 | 0.4 |
| Rep. Rate [Hz] | 120 | 10 | 60 |
| # Bunches/Pulse | 1 | 3000 | 1 |
| Avg. Beam Power [kW] | 0.36-1.8 | 650 | 0.2 |

## INJECTOR

A sketch of the XFEL injector complex is shown in Figure 3. Two injectors are foreseen. This increases the availability of the XFEL and facilitates independent injector tuning and development. The injector layout is similar to the present installation at TTF. It uses an RF-gun, directly followed by an eigth-cavty TESLA accelerating module. Each injector will be a equipped with a diagnostic section. This section consists of a FODO lattice which comprises four beam size measurement stations, allowing to measure the emittance and optical functions before entering the bunch compressor (four screen method) [7]. Using this setup, a projected emittance of 1.4 mm mrad has been regularly measured at TTF.

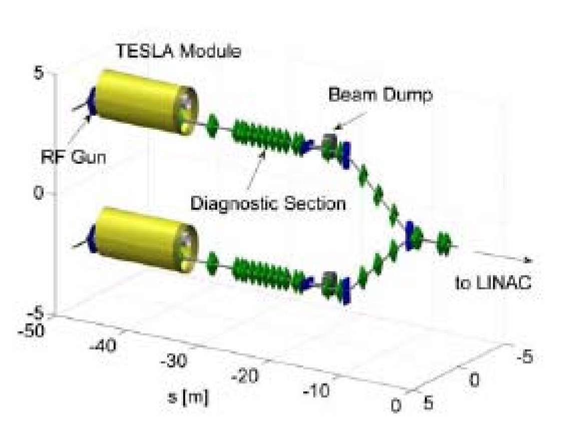

Figure 3: Injector layout of the XFEL

Figure 4 shows the development of the emittance along the XFEL injector as simulated with ASTRA. Further improvements of the gun are needed to reach the emittance goal of 1 mm mrad at 1 nC charge. This includes the processing and operation of the gun at higher gradients (presently 40 MV/m, foreseen 60 MV/m) and continuous improvements of the laser profile. These measures are implemented in the present upgrade of the Photo injector test stand in Zeuthen (PITZ) [8].

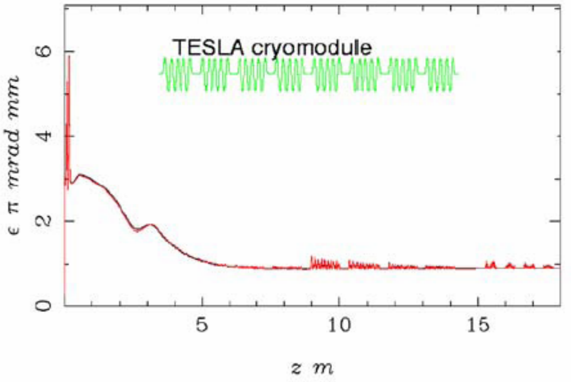

Figure 4: Development of transverse emittance in the XFEL injector (ASTRA simulation). Laser profile with uniform transverse distribution and longitudinal flat-top with 2 ps rise time.

An alternate approach to high-brightness electron beam generation is being pursued at SCSS using a low emittance HV-pulsed gun with a $CeB_6$-cathode and a reduced bunch charge level of 0.1 to 0.5 nC. An emittance of 1.1 mm mrad has been measured in their test facility [9].

The Paul Scherrer Institute (PSI) in Switzerland currently develops a Low-Emittance electron-Gun (LEG) based on field-emitter technology [10]. The target is a normalized transverse emittance of 0.05 mm mrad or less. Such a source is particularly interesting for X-ray FELs since it permits a reduction of the required beam-energy and hence, a reduction of the construction- and operational costs.

## BUNCH COMPRESSION

The large peak currents are reached with a bunch compression system. The basic layout is always very similar. Electrons are accelerated after the gun to an energy where space charge forces are small enough to not deteriorate the beam qualities. This acceleration is performed off-crest to add a momentum-longitudinal position correlation (chirp) to the bunch. In addition the bunch energy spread increases within the curved RF acceleration potential. A higher harmonic cavity system is then used to linearize the longitudinal phase space again, before the first bunch compression is performed [11]. After this a second acceleration takes place (again to mitigate space charge effects), and a second bunch compression is performed. Splitting the compression has several reasons: The first compression is performed as early as possible to decrease the nonlinear effects of the accelerating fields. Because of space charge effects the bunches are not compressed to the final peak current values. The second compression is thus at higher energies and weaker to decrease the coherent synchrotron radiation forces, which scale with the bunch compressor dipole bending strength and inversely with the bunch length.

The bunches are not fully compressed at the end of the second bunch compression. The remaining momentum-longitudinal correlation is taken out by the wake-fields in the main linac. This leads to subtle differences in the bunch compressor set-ups: With stronger wakefields in the main linac the LCLS can allow for a larger chirp and smaller $r_{56}$ leading to reduced CSR effects (see Table 2).

Figure 5 shows the initial and final longitudinal beam profile for the LCLS. Due to the longitudinal compression the bunch develops sharp spikes - or ‘horns’ - at the tail and the head. The reason for this is a combination of strong wakefields in the accelerating structures and the coherent synchrotron radiation wakefield. These spikes will lead to very strong wakefield effects in the undulator vacuum chamber. An alternative set of parameters with lower charge has been developed which reduces the spikes to a much smaller level [12].

Figure 6 shows the initial and final beam profile for the XFEL. Due to the smaller wakefields in the TESLA cavities and optimized settings of the bunch compressor parameters spikes can be avoided.

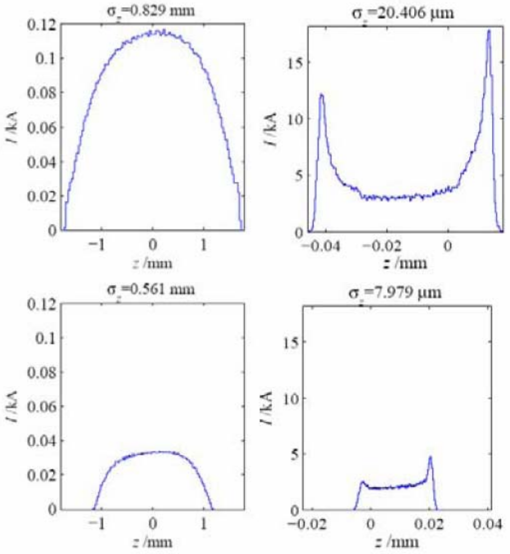

Figure 5: Initial (left) and final (right) longitudinal beam profile for the LCLS using a low charge (0.2 nC) in the bottom line and a high charge (1 nC) working point in the top line. The bunch head is at $z < 0$.

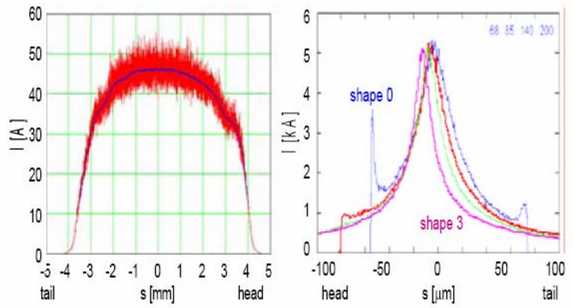

Figure 6: Initial (left) and final (right) longitudinal beam profile for the XFEL. The four colors in the left plot indicate the possibility of tuning the final beam distribution with the help of the orthogonal tuning ‘knobs’ constructed out of the first and higher harmonic RF parameters [13].

Table 2: Bunch Compressor Parameters

| | LCLS | XFEL | SCSS |
|---|---|---|---|
| Initial peak current [kA] | 0.1 | 0.05 | 0.04 |
| $1^{st}$ bunch compression stage | | | |
| Energy [MeV] | 250 | 500 | 450 |
| Compression | 4.3 | 14 | 15 |
| $r_{56}$ [m] | ≈36 | ≈90 | ≈50 |
| Peak current [kA] | 0.5 | 0.7 | 0.6 |
| $2^{nd}$ bunch compression stage | | | |
| Energy [MeV] | 4540 | 2000 | 790 |
| Compression | 8.8 | 7 | 5 |
| $r_{56}$[m] | ≈22 | ≈30 | ≈4 |
| Final peak current [kA] | 3.2 | 5 | 2-3 |

## MAIN LINEAR ACCELERATOR

The most striking difference between the X-ray FEL projects is the choice of the main accelerator rf. LCLS relies on the well proven SLAC linac. A basic S-band accelerating structure is 3 m long and comprises 84 cells. 4 structures are powered by one klystron, with a total of 77 klystrons (including spares) used for the LCLS main linac.

The SCSS main linac is based on C-Band technology developed for the Japanese linear collider project. This leads to higher gradients and thus shorter linac length. All mayor rf parts have been developed in the past years. The accelerating structure will use choke mode damped cavity cells [15] to effectively damp long range wakefields. This will allow the acceleration of multi-bunch beams as a future option for the SCSS. A first 1.8 m long C-band (with 100 cells) structure was successfully tested with high power in 2004. The 8 GeV linac will use 144 of these structures, grouped into units of 4. Each unit is fed by two 50 MW klystrons running in parallel.

The XFEL linac is based entirely on the technology which was over the past years developed by the TESLA collaboration as the most essential part of the R&D program towards a superconducting linear collider. The TESLA Test Facility (TTF) has demonstrated that superconducting 9-cell Nb cavities can be reliably produced and operated with beam with the XFEL design performance of 23MV/m. With the electro polishing (EP) method to improve the Nb surface quality, 9-cell cavities were tested at gradients of 35 – 40MV/m. The main linac for the XFEL will be built with the EP technique.

The main linac uses 116 12m long accelerator modules with 8 superconducting cavities each, grouped in 29 rf stations. The linac is housed in a tunnel (Figure 7) 15 – 30m underground. The klystrons are in the tunnel and connected to the modulators in a surface building by pulse cables. The required klystron power per station is 4.8MW, well below the maximum power of 10MW of the multi-beam klystrons developed in industry for the TESLA project. This will not only cover the power needs for operation at higher energies, but also allow operating the linac at higher repetition rates (and duty cycles) at lower energy (the main limitation then being the *average* power of the RF system).

In contrast to conventional linacs, with the superconducting accelerator technology even a continuous wave (CW, 100% duty cycle) operation of the linac is conceivable, although only at reduced energy/accelerating gradient in order to avoid excessive cryogenic load into the Helium at 2K. Such an option is not part of the initial stage of the facility, but becomes attractive if lower-emittance, high duty cycle beam sources become available. We estimate that with a gradient of 7 – 8 MV/m (~7 GeV beam energy) this mode of operation would be compatible with the foreseen cryogenic plant.

Table 3: Parameters for XFEL CW operation

| | |
|---|---|
| Beam Energy [GeV] | 6.5 |
| Gradient [MV/m] | 7 |
| Beam current [mA] | 0.18 |
| Bunch spacing [µs] | 5.5 |
| rf power/module [kW] | 20 (requires new low power rf system) |
| beam power [MW] | 1.2 |
| cryo load [kW] | 2.4 |

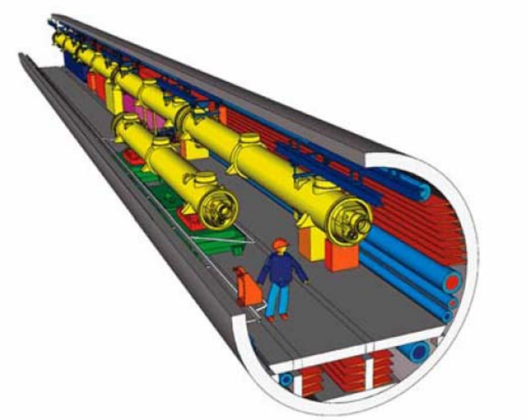

Figure 7: Layout of the XFEL accelerator tunnel

## UNDULATORS

All FEL projects use permanent magnet based undulator technology. Different philosophies are followed in view of gap variability and vacuum installation. The XFEL will use variable gap undulators to allow some independent tuning of the output radiation wavelength. In the case of the XFEL this allows a true multi-user facility with an independent choice of the radiation wavelength [16]. The SCSS Undulators will be placed inside the vacuum chamber, thus allowing for smaller gaps and shorter periods with higher K values. This technique has been pioneered at SPRING8. The possibility of opening the undulator gap has also the advantage that an alignment/diagnosis of individual undulator segments with spontaneous synchrotron radiation becomes possible. At the LCLS with their fixed gap devices this can be realized by moving the undulators sideways away from the vacuum chamber.

Table 4: Undulator parameters

| | LCLS | XFEL | | | SCSS |
|---|---|---|---|---|---|
| Half aperture [mm] | 2.5 | 3.8 | 3.8 | 3.8 | 1.75 |
| Period length [mm] | 30 | 35.6 | 48 | 56 | 15 |
| K-Value | 3 | 3.3 | 2.8-6.1 | 5.2-11 | 1.3 |

The undulator segments (3-5 m long) are embedded in a FODO lattice. Trajectory tolerances in the undulator sections are extremely tight. The rms deviation of the electron beam path should not exceed approx. 5 µm, the slope not 5 µrad. BPMs are aligned along a straight line using a laser system (Figure 8) or wire positioning system. Trajectory control is performed by moving the focussing quadrupoles to steer the beam through the BPM center or to minimize the dispersion (beam based alignment).

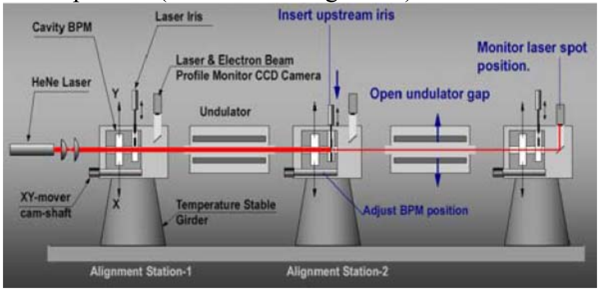

Figure 8: BPM alignment system for SCSS. The image of an alignment iris attached to the RF-BPM can be observed with an HeNe laser beam inside the beam pipe [4].

## WAKEFIELDS

Wakefields play an important role for the final bunch shape of short bunches. The wakefields of the accelerating structures lead for instance to the current spikes at the head and tail of the LCLS and SCSS bunches. In the small gap undulator vacuum chambers resistive wall wakes, geometric wakes and surface roughness wakes play an important role. Reference [18] gives a comprehensive overview.

By proper design of the vacuum chamber components it is possible to reduce the contribution of the geometric wake to a fraction of the resistive wake (see Figure 9). The same is true for the surface roughness wake, which amounts to 10-20% of the resistive wake for a roughness of 300 nm [20].

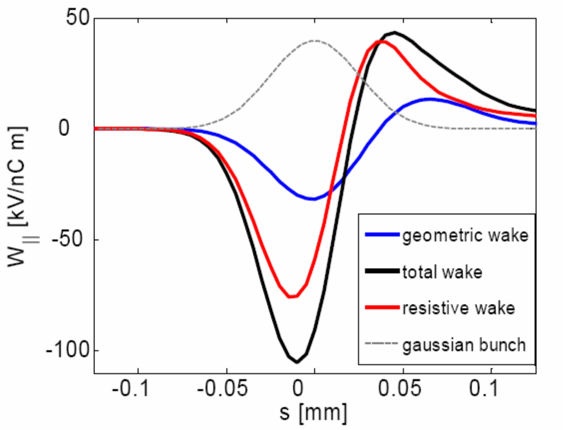

Figure 9: Wake field contributions including the geometric wakes (tapered absorber, pump, bellow, flange gap) and the resistive wake (25 µm Cu, 4.5 mm radius) of one segment of the XFEL undulator section [19].

For the resistive wake the material properties of the vacuum chamber play e a crucial role. So-called AC-conductivity effects differ for different materials like Cu and Al. In the case of the LCLS with its strong leading spike this leads to the conclusion that an Al vacuum pipe may be of advantage because the AC wake is damped faster [21]. In the case of the XFEL with its ‘Gaussian’ bunch shape this effect is negligible (see Figure 11).

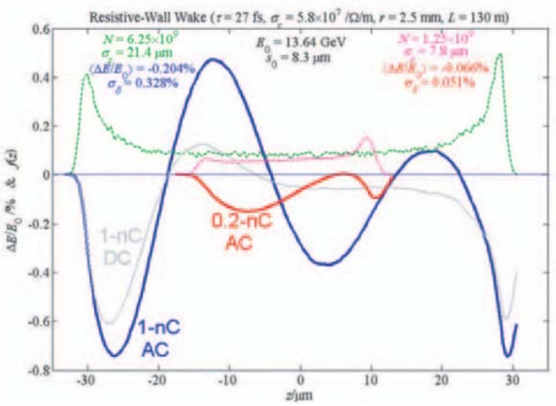

Figure 10: Resistive Wake in the LCLS undulator for the 1 nC (blue) and 0.2 nC setup [12].

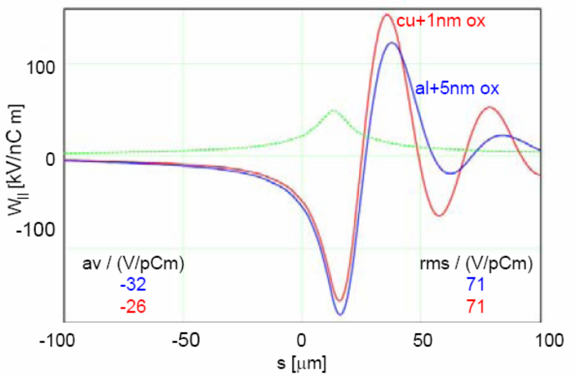

Figure 11: Resistive and Surface Roughness Wake for bunch shape 3 (see Figure 6). Beam pipe radius is 3.8mm, roughness 300 nm.

## OUTLOOK

X-ray free electron lasers will become reality in the upcoming years. While many of the accelerator physics challenges are understood, the focus will move towards commissioning and operation of these facilities.

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