LAYOUT OF THE BEAM SWITCHYARD AT THE EUROPEAN XFEL

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Abstract

A unique feature of the European XFEL will be the possibility to distribute electron bunches of one beam pulse to different FEL beam lines. This is achieved by using a combination of fast kickers and a DC septum. Integration of a beam abortion dump allows a flexible selection of the bunch pattern at the FEL experiment, while the superconducting linear accelerator operates with constant beam-loading. We describe the principal scheme, the geometrical and optical layout and deal with stability and technical issues like the fast kicker development.

INTRODUCTION

The European XFEL [1] has been planed as a multi-user facility from the beginning. The initial extension stage foresees two electron beam-lines serving 3 SASE and 2 spontaneous undulators in total. An additional beam distribution can be added in the future. The superconducting driver linac of the FEL can deliver up to 600 μs long bunch trains with a repetition rate of 10 Hz and a maximum energy of 20 GeV [2]. To make full use of the available beam, fast switching between the electron beam-lines is foreseen within a bunch train. In addition, the bunch repetition pattern can be adjusted individually for each beam-line. This is obtained by means of two kicker-septum combinations, distributing bunches either towards one or another electron beam-line (once per train), or into a beam dump (as desired). This scheme allows the operation of the upstream accelerator (injector, bunch compression, linac, collimation, and intra-bunch transversal and longitudinal feedback system) with constant bunch frequency, thus increasing the stability of the overall system.

BEAM LINE LAYOUT

The linear optics layout is constraint by the following aspects:

- Space requirements for the bifurcations into the several beamlines.
- Matching the in- and out-going phase space.
- Unperturbed beam transport of a 3 σ beam for energy deviations of up to ±1.5% to the undulator and beam transport for a 50 σ beam for up to ±2.5% energy deviation to the beam dump.
- Optimized placement of kicker and septa to minimize the required kick strength while maximizing the available amplitude at the septum.

The geometrical layout of the section is sketched in Fig.1 with the beam coming out of the linac and collimation section from the left. The first set of kickers offsets the beam horizontally into a Lambertson type septum magnet that deflects the beam upward to the dump-line. The dump-line eventually bends downwards again (in between the two beam transport lines that lead to the undulators).

After the dumped beam extraction the next set of kickers deflects the beam horizontally into a horizontal deflecting DC septum leading into the beam-line ‘TD1’, that serves the SASE undulator SASE2 and two spontaneous radiators. The un-kicked beam goes straight into the ‘TD2’ line, serving SASE undulators SASE1 and SASE3.

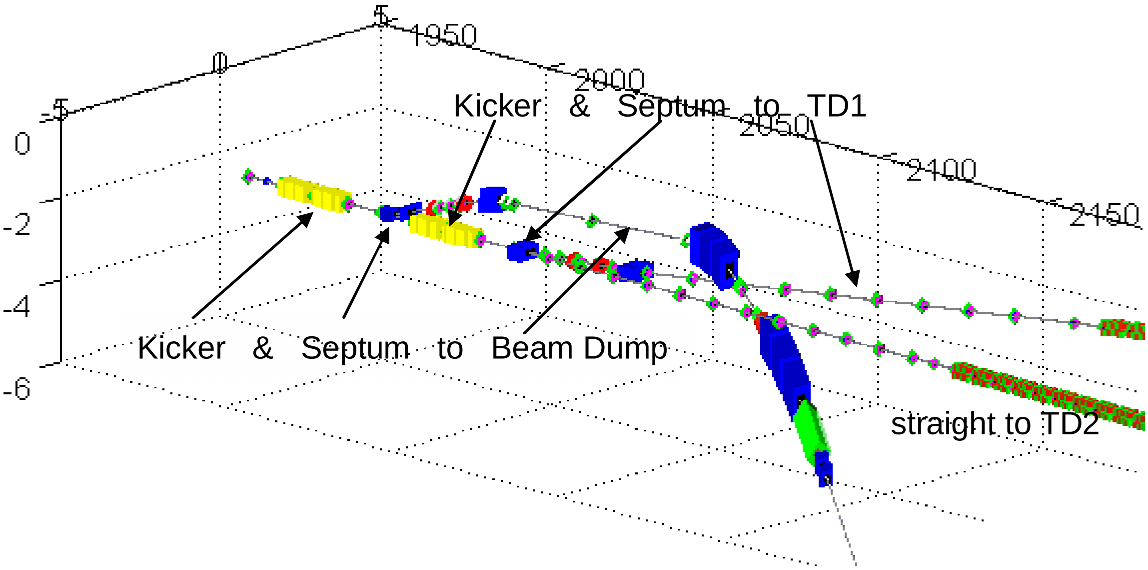

Figure 1: Sketch of the XFEL switchyard section. Fast kickers are shown in yellow, septum and bending magnets are blue, quadrupoles green.

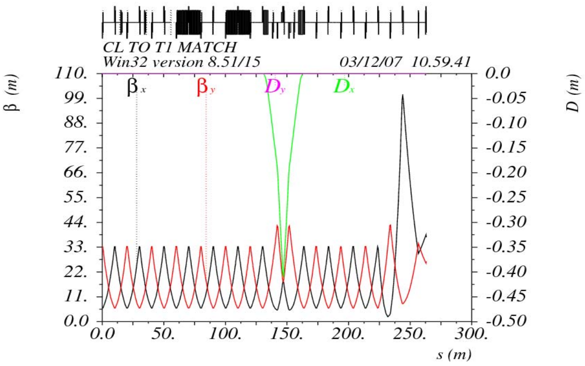

Figure 2: Linear optics along the switchyard and the deflection into the TD1 beamline.

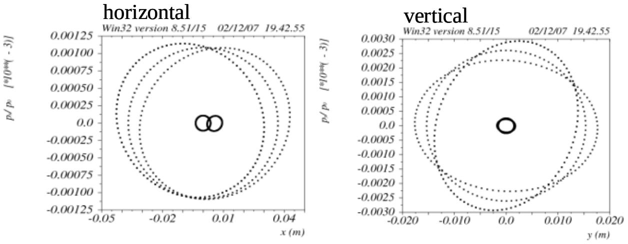

Figure 3: Tracking of 0.1σ and 1σ ellipses through the deflection arc towards the TD1 beamline.

The required trajectory offset at the septum is given by the physical dimensions of the septum bar (including the vacuum chamber) and the required beam stay-clear. The beam stay-clear is ultimately defined by the collimation depth of the upstream collimation system which protects the downstream hardware (undulators and septum).

The optimization of the kick strength requires maximizing the R_{12} between the kicker and the septum. The needed kick strength is

$$R_{12}\theta \geq x_{septum} + 2 \cdot x_{beamstayclear} \qquad (1)$$

or, using linear beam transport theory and Courant-Synder notation:

$$\theta \geq \frac{1}{\sqrt{\beta_k \beta_s}\,\cos(\phi_s - \phi_k)} \left(x_{septum} + 2 \cdot n_{cl} \cdot \sqrt{\frac{\varepsilon_n}{\gamma}\beta_s} \right) \qquad (2)$$

with β, ϕ beta-function and phase advance, x_{septum} the septum bar width and n_{cl} the collimation depth in units of beam sigma.

A phase advance of 90^{o} and a large beta-function at the kicker and septum location is optimal. On the other hand, good chromatic properties are required which is in contradiction to large beta-functions and phase advances within a short distance. A good compromise is a 90deg FODO lattice with a cell length (20 m) matched to the geometric requirements of the distribution system (see Figure 2).

The chromatic properties of the beam transport through this system are shown in Figure 3, where 1σ ellipses have been tracked for ± 1.5% through the deflection arc towards the TD1 beamline. Two sextupoles are included in the dispersive section to provide higher order dispersion correction. The beam distortion is acceptable and the small centroid motion (in the order of 0.1 σ) can be corrected by the intra-bunch feedback system.

DEFLECTING ELEMENTS

Kickers

Two types of fast elements will be used:

- A flat top kicker with a pulse length of 300 µs, an amplitude stability of better than 3×10^{-4} and a rise or fall time of 20 µs (corresponding to about 100 bunches).
- A kicker with a short rise-/fall-time of below 100 ns that is capable of kicking single bunches out of the train. These bunches will be dumped and the required amplitude stability is only 1×10^{-2}.

The kickers themselves are not finally specified and can be either strip-lines mounted around a ceramic chamber or in-vacuum strip-lines as used for instance for the PETRA III feedback or developed for CTF 3. The length is in the order of 1 m, leading to a fast field build-up. The necessary total kick strength is obtained by installing the desired number of kickers in a row. The kicker/vaccum chamber inner aperture radius is reduced form the standard 20 mm beam-pipe radius to 10 mm. The impact of resistive and geometric waves on the energy spread of the bunch has been calculated and normalized to the energy spread induced by the short range wake of the subsequent undulator SASE2. The contribution of the step in the vacuum system amounts to 0.72%, while the resistive and roughness wake of the sputtered ceramic chamber contributes 0.22% per meter chamber to the energy spread at the end of SASE2 [4].

The flat-top pulser consists of a capacitor array (0.2 F) that is charged by a standard laboratory power supply and discharges via a fast IGBT switch. The switch limits the obtainable flat-top current to about 250 A, yielding a field of approx. 13 mT. Thus four 1m long kickers will provide a sufficient beam kick at the maximum energy of 20 GeV. An additional kicker/pulser will be installed for redundancy reasons.

The measurement of the pulser stability to a sub-10^{-4} level is difficult with standard current transformers. To this purpose, two test-pulsers have been built and connected to the opposite ends of separate strips of a strip-line kicker. The difference current is measured with a current transformer mounted around both strips. The result of such a measurement is displayed in Figure 4, where a histogram of 3.000 pulses (1 hour of 1 Hz operation) is plotted, showing a relative peak-to-peak variation of 2.3×10^{-4} and an RMS of 3.2×10^{-5}.

The relative slope of the flat top itself over the 300 µs pulse is about 1.8 %. This value can be reduced by adding capacitors or correcting the trajectory error with a feed forward system

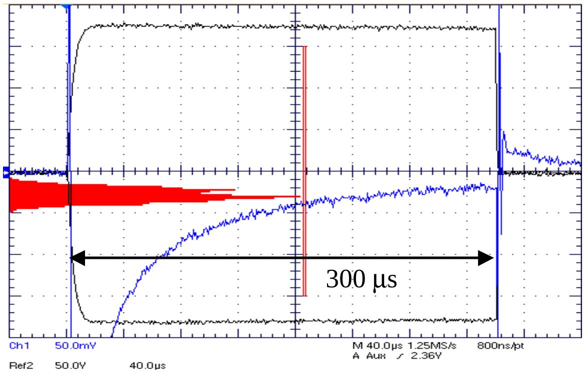

Figure 4: Pulse shape of the two flat top pulses (black) and difference measured by the current transformer (blue). Note that the scale of the two curves differs by a factor 1000. The histogram on the left shows the pulse to pulse variation of 3.000 pulses with a peak-to-peak variation of $2.3{\times}10^{-4}$.

The fast pulser has less demanding amplitude stability requirements. The pulser has been realized with five Behlke HTS 80-12UF high-voltage switches in parallel. The amplitude is matched for each switch separately with appropriate resistors. The pulse current can be up to 80 A, yielding 4.2 mT field amplitude. In total 16 0.5 m long kickers will provide the beam kick at the maximum energy of 20 GeV. A relative amplitude jitter of <0.5% RMS has been measured both in the laboratory and with beam at FLASH. The biggest challenge appears to be the current ripple after the pulse. The specification asks for residual field amplitude of less than $3{\times}10^{-4}$ relative to the main amplitude. A residual field of about 0.7% has been measured (see Figure 5), which depends on the previous number and frequency of pulses.

Further development includes the investigation of a commercial fast pulser that can deliver 5 MHz bursts.

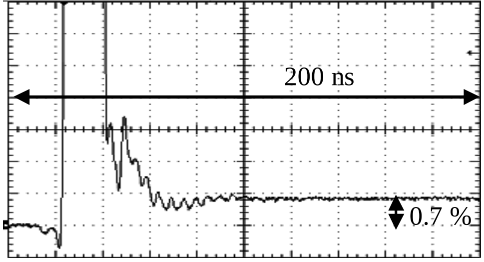

Figure 5: Measurement of the fast pulser current, showing a plateau of 0.7% of the maximum amplitude after 200 ns.

Septa

A Lambertson septum will be used for the first deflection into the beam dump. This requires a kick in the horizontal plane and deflects upward in the vertical plane. Dispersion is created in both planes, but as the beam quality is not an issue in the dump line this is acceptable. The contrary is true in the deflection towards the TD1 undulators. Here the beam trajectory should not vary more than a few microns for an energy variation of ±1.5%. This puts stringent requirements on the residual dispersion created by the deflection system. The deflection is thus solely in the horizontal plane, using a DC septum. The relative stability for the DC deflecting elements is in the order of $1{\times}10^{-6}$.

Table 1 summarizes the deflection element properties.

Table 1: Deflection Element Specifications

	Deflection to Beam Dump	**Deflection to TD1 Undulator Line**
	Kicker	
Pulse Form	Burst	Flat top
Repetition Rate	$5{\times}10^{6}$ Hz	10 Hz
Max. Pulse Width	$200{\times}10^{-9}$ s	$300{\times}10^{-6}$ s
Rise/Fall Time	$< 100{\times}10^{-9}$	$\approx 20{\times}10^{-6}$ s
Rel. Amp. Stability	0.01	$3{\times}10^{-4}$
Rel. Residual Ripple	$3{\times}10^{-4}$	$3{\times}10^{-4}$
Kick angle	0.5 mrad	0.5 mrad
Int. Field at 20 GeV	33.4 mT m	33.4 mTm
Kicker aperture	24	24
Kicker Type	Strip Line	Strip Line
Kicker active length	0.5 m	1 m
Number of kickers	16	5
Pulser Voltage	8 kV	100 V
Pulse Current	80 A	250 A
	Septum	
Septum Type	Lambertson	DC
Deflection angle	35 mrad	20 mrad
Device Length	4 m	4 m
Int. Field at 20 GeV	2.35 Tm	1.33 Tm
Septum Bar Width	5 mm	5mm
Rel. Amp. Stability	$1{\times}10^{-4}$	$1{\times}10^{-6}$

SUMMARY

The beam switchyard of the European XFEL will allow fast switching between the different SASE beamlines. Careful optics design ensures stable and flexible operation of the system. Switching elements have been developed to meet the demanding stability requirements. Remaining challenges are the development of a stable high-current DC septum and the reduction of the after pulse ripple.

REFERENCES

[1] M. Altarelli et. al., “The Technical Design Report of the European XFEL”, DESY 2006-097.

[2] The maximum energy is only reachable with a fully equipped linac. The start-up scenario will allow to reach the nominal operation energy of 17.5 GeV with 84 TESLA modules in the main linac.

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[4] I. Zagorodnov, “Impedance Budget from LINAC to SASE2”, http://www.desy.de/xfel-beam/talks_2007.html.