

# HIGH STABILITY RESONANT KICKER DEVELOPMENT FOR THE SwissFEL SWITCH YARD

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## Abstract

The SwissFEL is a linac-based X-ray free electron laser facility under construction at the Paul Scherrer Institute. The facility will provide femtosecond, high brightness X-ray pulses for fundamental and applied science research. To increase facility efficiency, a double bunch operation is planned to serve simultaneously two experimental stations at the full linac repetition rate. The main linac will accelerate two electron bunches spaced 28 ns apart and a fast and stable deflecting system will be used to separate the two bunches into two different undulator lines. The deflecting system uses a novel concept based on resonant kicker magnets. A prototype kicker magnet and its control system were designed and built. Since stability is crucial, the stability performance of the prototype was studied. The peak to peak amplitude stability of  $\pm 11$  ppm (3.5 ppm rms) was achieved, which is well within the FEL tolerance of  $\pm 80$  ppm. The layout of the deflecting system and the key design parameters are also presented.

## INTRODUCTION

The Swiss X-ray Free Electron Laser (SwissFEL) [1] is a 4<sup>th</sup> generation light source under construction at Paul Scherrer Institute (Switzerland). It is based on a linear electron accelerator with maximum energy of 5.8 GeV and will be a user operated facility. It will produce short (2 to 20 fs) and high brightness (up to  $6 \cdot 10^{35}$  photons $\cdot$ mm<sup>-2</sup> $\cdot$ mrad<sup>-2</sup> $\cdot$ s<sup>-1</sup>) X-ray pulses covering the spectral range from 1 to 70 Å [2]. In order to make the facility more efficient the main linac operates in two electron bunch mode. Each RF pulse will accelerate two electron bunches, separated in time by 28 ns. At 3.0 GeV beam energy a high stability deflector system separates

them and sends them to two additional linacs and respectively to two undulator lines. This allows simultaneous operation of two experimental stations at the full repetition rate of the machine (100 Hz). The SwissFEL layout is schematically presented in Fig. 1.

## RESONANT KICKER SCHEME

A novel approach using fast high Q-factor resonant deflecting magnets is being used for high stability, reliable and fast bunch separation. The main component of the deflecting system is the composite kicker magnet. It consists of two vertical resonant kicker magnets (kickers) and three compensating vertical DC dipole magnets (dipoles). The two kickers are high Q-factor LC resonators tuned to frequency with half period equal to the bunch separation time (17.857 MHz). They are synchronously excited and after they reach their nominal current amplitude (500 A peak-to-peak) the two electron bunches arrive and are deflected up and down ( $\sim \pm 1$  mrad) by the positive and negative maximum of the magnetic field created by the oscillating magnet current. This process is illustrated in Fig. 2. The three compensating dipoles steer the “down deflected” beam (straight beam) back to the machine axis. After some drift distance (with quadrupole magnets) the “up deflected” beam (deflected beam) enters a DC septum magnet 10 mm off axis [3]. The DC septum is a Lambertson type dipole magnet that bends the deflected beam 2° in the horizontal plane and creates the final angular separation between them. A system of DC dipole magnets brings the deflected beam back into the machine horizontal plane and steer it parallel to the machine axis at 3.75 m distance.

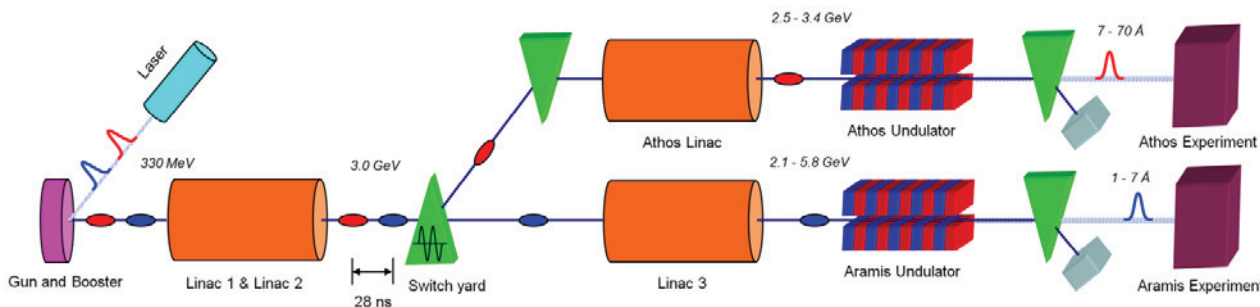


Figure 1: Schematic representation of SwissFEL double bunch operation scheme.

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In order to ensure the required beam position stability the shot-to-shot stability requirement for the entire system is set to be better than  $\pm 5$  ppm of the total  $2^\circ$  deflection. This sets the stability requirement for the composite kicker to be better than  $\pm 80$  ppm [3].

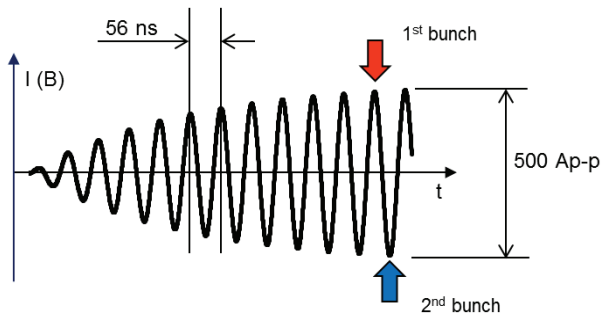


Figure 2: Deflecting current is slowly excited in the resonant deflecting magnet. The two bunches arrive at the positive and negative maximum of the resonating current.

### BEAM TRAJECTORIES

Since the total angular separation provided by the composite kicker (K1 and K2) is only in the order of  $\pm 1$  mrad the two beams continue to travel very close to the machine axis down to the entrance of the septum magnet (S). They share the same machine optics components and travel in the same vacuum chamber. The three compensating dipoles (D1, D2 and D3) are set in order to steer the straight beam back to the machine axis. In this way the machine optics components do not introduce significant trajectory changes to the straight beam.

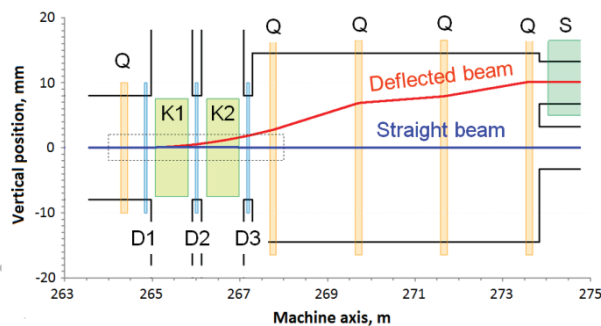


Figure 3: Beam trajectories of the straight and deflected beam. The color rectangles represent the corresponding magnet field regions.

However this is not the case for the deflected beam. It diverges slightly from the machine axis and its trajectory is altered by the quadrupole magnets (Q). The net result is that the total deflection of the beam is reduced by about 30%. Figure 3 shows the beam trajectories through the composite kicker and down to the septum. Figure 4 gives an enlarged view of the beam trajectories in the composite

kicker region (the area indicated by dotted line rectangle in Fig. 3).

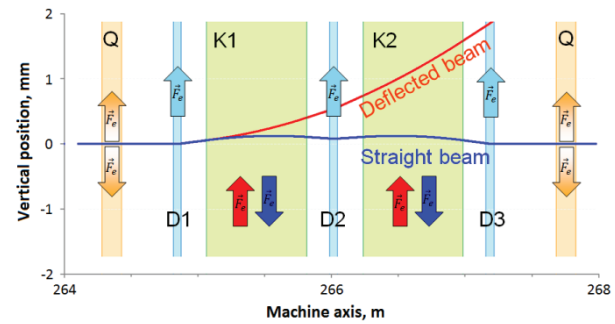


Figure 4: Enlarged view of the trajectories through K1 and K2 region. The color rectangles represent the corresponding magnets' field regions and the arrows represent the direction of the electron deflection force.

### OPERATION MODES

Using different settings of the composite kicker components it could be operated in different modes. The operation modes are divided in two groups: "Operation" and "Diagnostics". In the "Operation" modes the beams are separated and delivered to the two different beam lines. In the "Diagnostics" modes the two bunches are not separated. Certain components are turned off to enable machine tests or development. The figures below give a schematic view of the beam trajectories and the spatial constraints along the composite kicker region. The horizontal and the vertical axis units are arbitrary. The numbers above each particular component gives its relative deflection strength.

#### Operation Modes

Figure 5 and Figure 6 illustrate the two main operation modes. In this case the beams are delivered to the corresponding beam lines. A phase inversion of the kickers allows to control which beam is deflected and which goes straight.

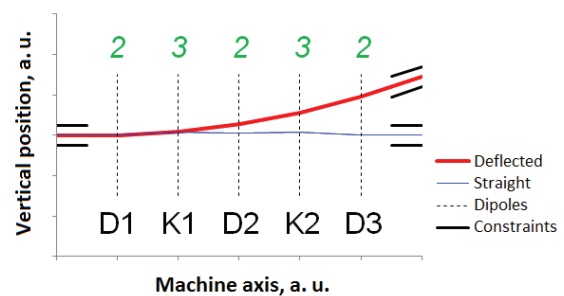


Figure 5: Main operation mode. The beams are separated and delivered to the corresponding beam lines. The numbers above each particular component gives its relative deflection strength.

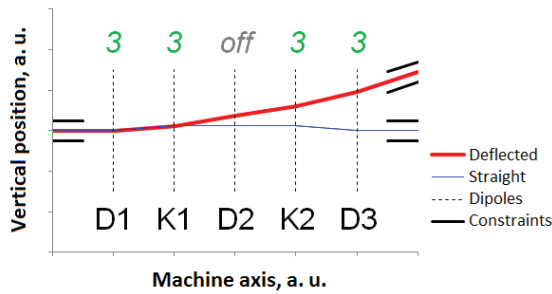


Figure 6: Alternative operation mode with the middle of the compensating dipole magnets off.

**Diagnostics Modes**

The set of diagnostic modes enables jitter measurements by sending both bunches to only one beam line. Since the stability of the system is crucial these modes can be used to identify instability in different parts of the composite kicker as well as to further develop and upgrade the machine.

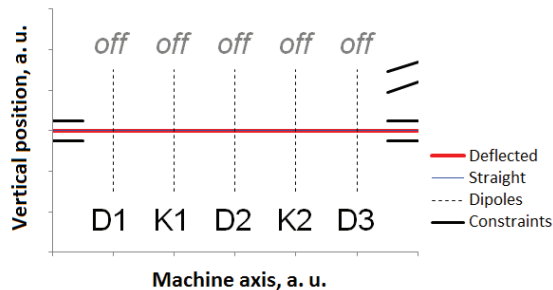


Figure 7: All magnets off. No beam deflection. Both bunches go straight.

Figure 7 shows a “trivial” state of the deflection system (all magnets off). In this mode the residual beam instability (not driven by the deflection system) can be evaluated. As well, this mode could be used for testing of the straight beam line (Aramis).

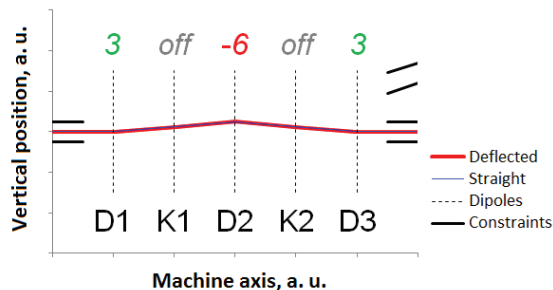


Figure 8: All kickers off. Chicane formed by the compensating dipoles. Both bunches go straight.

The mode in Fig. 8, permits a stability measurement of the compensating dipoles.

Figure 9 shows the mode that could send both bunches to the second beam line. As well, this mode could be used for testing of the second beam line (Athos).

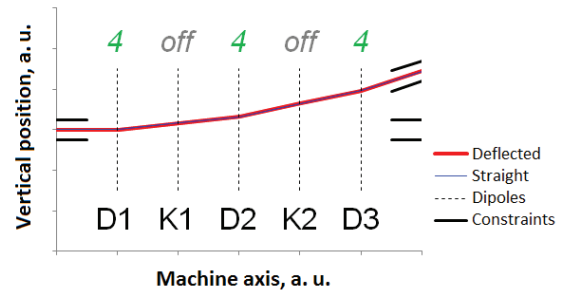


Figure 9: All kickers off. The deflection is provided by the compensating dipoles. Both bunches are deflected.

This list of modes is not exhaustive. The modes above illustrate the operation flexibility of the composite kicker.

**KICKER MAGNET PROTOTYPE**

A prototype kicker and its control system was built and tested.

Resonance systems can convert phase noise into amplitude noise. In order to have stable operation of the resonant kicker a low phase noise driver was designed. The driver supply voltage is controlled with 1ppm resolution. In order to avoid radiation concerns all the active electronics will be outside of the beam tunnel.

Figure 10 shows the prototype kicker in the lab.

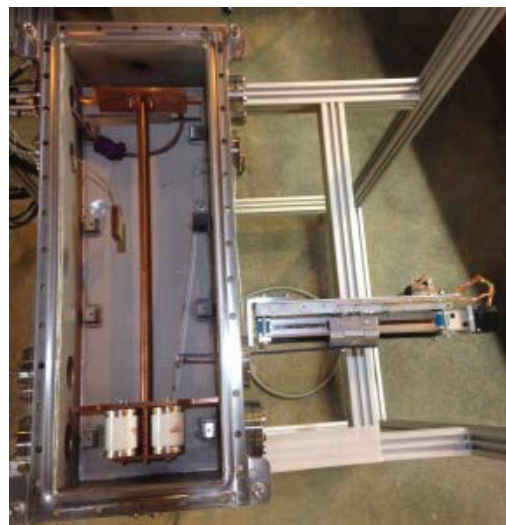


Figure 10: Prototype kicker resonator in the vacuum tank.

The prototype kicker magnet was tested for amplitude and phase stability. This system also provided a test bed for temperature, resonance tunability and mechanical vibration stability studies.

## CALIBRATION AND STABILITY MEASUREMENTS

A high precision amplitude measurement system was developed in order to evaluate the stability of the kicker magnet. It is based on balanced measurement method and it is capable of measuring the amplitude stability of the kicker down to several ppm. The performance of a balanced system depends strongly on the used reference. A high stability voltage source was developed with stability of 0.35 ppm rms for more than 80 h [3]. Care was taken to ensure the proper measurement sensitivity since the incremental sensitivity could significantly differ from the full-range sensitivity. Figure 11 shows the calibration of the measurement system using 50 ppm incremental steps.

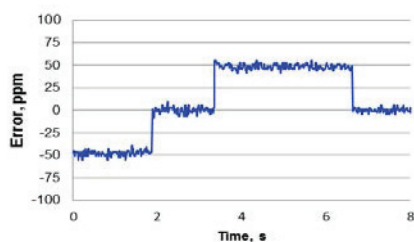


Figure 11: Calibration of the measurement system using 50 ppm incremental steps.

The shot-to-shot amplitude stability of the kicker prototype was measured to be  $\pm 9$  ppm (3.0 ppm rms) and 11 ppm (3.5 ppm rms) with the slow amplitude feedback respectively *off* and *on* [3]. The results are shown in Fig. 12 and Fig. 13.

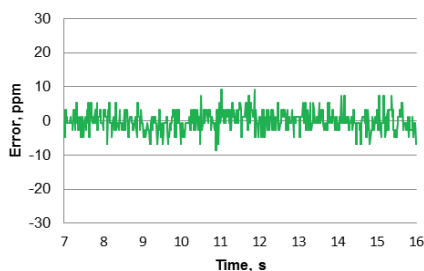


Figure 12: Kicker prototype amplitude shot-to-shot stability  $\pm 9$  ppm (3.0 ppm rms) with slow feedback *off*.

Measured time jitter of the kicker resonance waveform was  $\pm 25$  ps peak-to-peak corresponding to  $\pm 2$  ppm peak-to-peak amplitude jitter. This value is small compared to the amplitude jitter, thus the time jitter contribution could be neglected [3].

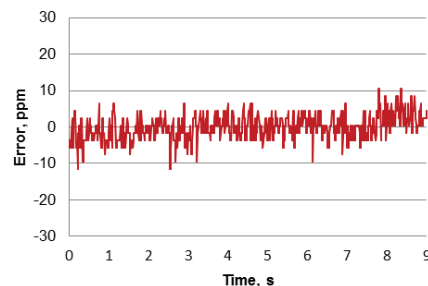


Figure 13: Kicker prototype amplitude shot-to-shot stability  $\pm 11$  ppm (3.5 ppm rms) with slow feedback *on*.

## SUMMARY

In order to increase the facility efficiency the SwissFEL will operate in double bunch operation accelerating two electron bunches 28 ns apart in one RF pulse. A novel high precision beam deflecting system based on high Q-factor resonant kicker magnets separates the bunches and sends them to two independent beam lines. The shot-to-shot stability of the resonant kicker magnets is crucial. A prototype kicker magnet was built and characterized. The measured shot-to-shot stability of the prototype was  $\pm 9$  ppm and  $\pm 11$  ppm peak-to-peak with slow feedback respectively *off* and *on*. Both results are well within SwissFEL tolerances ( $\pm 80$  ppm peak-to-peak). This gives confidence that this novel design approach is viable for the SwissFEL project.

## REFERENCES

- [1] SwissFEL website: <http://www.psi.ch/swissfel>
- [2] "SwissFEL Conceptual Design Report", PSI Bericht Nr. 10-04, April 2012, [ftp://ftp.psi.ch/psi/SwissFEL\\_CDR/SwissFEL\\_CDR\\_V20\\_23.04.12.pdf](ftp://ftp.psi.ch/psi/SwissFEL_CDR/SwissFEL_CDR_V20_23.04.12.pdf)
- [3] M. Paraliiev, C. Gough, "Stability Measurements of SwissFEL Resonant Kicker Prototype", *Proc. 2014 IEEE Int. Power Modulator and High Voltage Conf.*, Santa Fe, NM, USA, 2014