RESONANT KICKER SYSTEM WITH SUB-PART-PER-MILLION AMPLITUDE STABILITY

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Abstract

High stability resonant kicker magnet systems have been developed as part of the fast electron beam switching system of Swiss Free Electron Laser (SwissFEL). They are designed to separate two closely spaced electron bunches (28 ns apart) accelerated in one RF macro-pulse and to send them to two separate undulator lines. High shot-to-shot amplitude stability is required to minimize the disturbance of the electron beam trajectories and to ensure stable X-ray lasing. The stability and speed was unlikely to be achieved by standard pulsed systems and a novel 18 MHz, lumped-element resonator deflector with high Q was developed. It is driven into resonance by a specialized pulsed RF driver. At resonance, the circulating currents can approach 300 A and the resulting magnetic field gives the required deflection to the electron bunches. The advanced DC offset measurement system is also described in this paper. The measured stability reached less than 1 ppm (10^{-6}) rms, well within the project requirements.

INTRODUCTION

The Swiss X-ray Free Electron Laser (SwissFEL) [1] is a 4th generation, linear electron accelerator based, light source under construction at the Paul Scherrer Institute (Switzerland). It will produce short (2 to 20 fs) and high brightness (up to $6{\cdot}10^{35}$ photons$\cdot$mm$^{-2}\cdot$mrad$^{-2}\cdot$s^{-1}) X-ray pulses covering the spectral range from 1 to 70 Å [2]. To increase facility efficiency the main linac accelerates two closely spaced (28 ns apart) electron bunches in one RF macro-pulse. At 3.15 GeV beam energy they are separated by high stability beam switching system and they are sent to two additional linacs and two undulator lines, with the names “Aramis” and “Athos”. This allows two independent user experimental stations to operate at the full machine repetition rate. Figure 1 shows schematically SwissFEL two bunch operation mode.

MOTIVATION

Fast acting switching device is needed in order to separate the closely spaced electron bunches. A conventional step function kicker, with rise time in the order of 20 ns will require several tens of kilovolts operating voltage. The combination of high voltage and fast rise time narrows the possible switching solutions. The chosen resonant kicker solution relaxes the voltage requirements of the driving system, making possible to use entirely solid state technology. The high Q resonance circuit inherently filters out the broadband noise providing for finer amplitude and phase control. Also, a resonant kicker system will not suffer rise time degradation due to skin effect. This was the motivation to use a novel resonant kicker technology in SwissFEL switchyard.

BEAM SWITCHING

SwissFEL beam switching system consists of two fast high Q-factor resonant deflecting magnets (kickers), three compensating DC dipoles and Lambertson DC septum. The kickers are tuned to a frequency (17.86 MHz) with a period twice larger than the bunches’ separation time and run synchronously with the electron bunches.

One bunch arrives at the positive maximum of the kickers’ oscillating current and it is deflected upwards. Its total deflection, due to the kickers and the compensating dipoles, is ~2 mrad. After some drift distance (with quadrupole magnets) this bunch enters the Lambertson septum magnet 10 mm off axis vertically. The septum further deflects the bunch 2° sideways towards the Athos beamline.

The other bunch arrives at the negative maximum of the kickers’ oscillating current and it is deflected downwards. The compensating dipoles bring the bunch back to the original machine axis and it continues straight to the Aramis beam line [3].

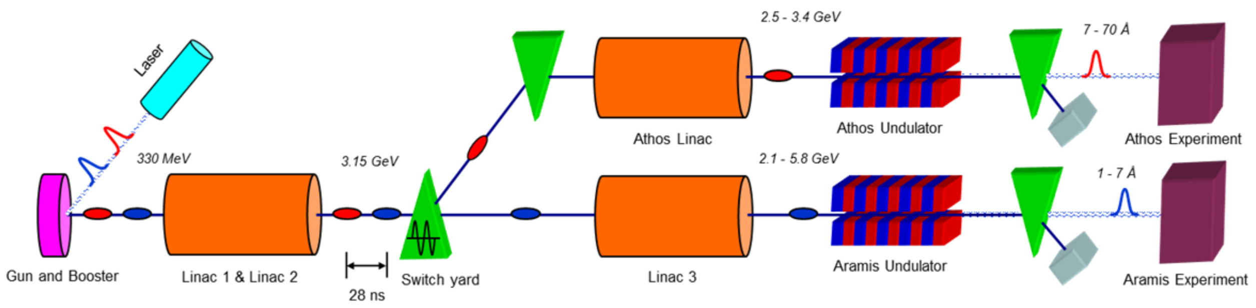

Figure 1: SwissFEL Two bunch operation mode.

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KICKER SYSTEM

To achieve the required beam deflection two identical kicker systems are used. Figure 2 shows an overview of the kicker system.

Synchronization Block

In this novel approach, the kicker's deflection is not constant in time (a step function) but a sine wave. This makes the proper timing of the devices crucial for their correct operation. Moreover the kicker magnets are high Q-factor resonators and they need time to reach steady state resonance amplitude before they are ready to deflect the electron bunches. The synchronization block takes a trigger signal about 50 µs before the beam arrival time from the conventional accelerator timing system and resynchronizes it with a high stability RF reference. ECL logic provides the necessary low jitter signals for the rest of the system. Synchronization block monitors the basic pulsed parameters programed by the operator (like max. pulse duration and max. repetition rate) and gives a warning if the limits are exceeded. It has a built-in "race condition" detecting mechanism as well.

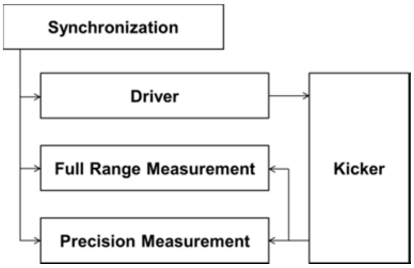

Figure 2: Block diagram of the Kicker system.

Driver

The driver provides high amplitude stability and low phase noise RF power to excite the kicker magnets. The output MOSFET RF power stages are powered by a precision, programmable, voltage regulator with 1 ppm resolution. The driver is temperature stabilized by high precision (±0.1°C) water circuit.

Kicker

Figure 3 shows the kicker lumped LC resonator, consisting of two 20 mm diameter copper bars for the inductance and two vacuum capacitors. Although the driving voltages are not very high, at fully developed resonance the ends of the kicker's conductors can reach up to 15 kV. The average dissipated power in the copper bars (resistive loss) is small (~20 W) but due to lack of convection cooling in vacuum, a thermal conduction path should be provided in order to stabilize the resonator's temperature. A series of machinable ceramic supports were used to provide the electrical insulation and the required thermal conduction. The base of the resonator is temperature stabilized by high precision (±0.1°C) water circuit. Nevertheless a couple of hours of operation are needed for the resonator to reach steady state. Movable vanes are used to tune finely the frequency of the resonator. Care is taken to reduce the mechanical vibration of the resonator since this will directly affect the stability of the magnet. Conductors' joints of the resonator are provided with "knife" edges in order to ensure a well-defined and stable electrical contact. Even so, experience shows that after assembly, the magnet should be operated for about a day before it stabilizes electrically.

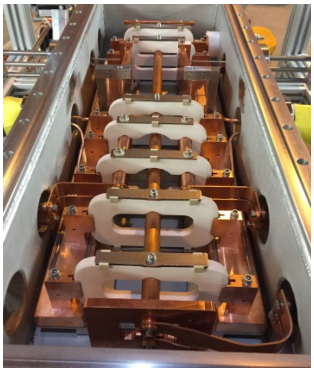

Figure 3: Kicker resonator inside the vacuum tank.

Full Range Measurement System

The Full Range Measurement (FRM) system provides amplitude and phase information about the oscillating current of the kickers. It is based on fast (250 MHz) high resolution (16-bit) ADCs interfaced by fast FPGA (Virtex 6). Digital synchronous detection and signal processing is used to get amplitude and phase with high resolution. It was found that signal to noise ratio is basically limited by the 1/f performance of the ADC chips and even with extensive averaging of two ADCs in parallel, only about 10 ppm could be achieved [4].

Precision Measurement System

For higher performance measurement than with the FRM, a complementary offset based Precision Measurement System (PMS) was designed and built [5]. High stability programmable (1 ppm resolution) DC offset is subtracted from the measured signal and the difference is amplified and measured. In this way, at the expense of measurement dynamic range reduction, higher measurement resolution and lower noise floor could be achieved. PMS is temperature stabilized by high precision (±0.1°C) water circuit. Using statistical analysis [6], the noise floor of the built PMS is evaluated to be ~0.8 ppm.

AMPLITUDE STABILITY

Unwanted slow amplitude drifts can be corrected to a large extent using different feedback schemes. However pulse-to-pulse amplitude jitter cannot be predicted or corrected due to its statistical characteristics and so this gives the limiting factor in building high stability pulsed systems. Another complication is the combination of pulse-to-pulse stability of the device under test (DUT) and the measurement system itself. This makes the development of high stability systems a complex iterative process, cycling between perfecting the DUT and the measurement system.

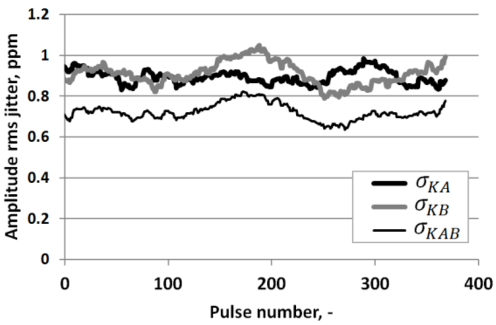

Figure 4: Running rms amplitude jitter of 100 consecutive kicker pulses measured with system A, system B and the average of A and B.

Figure 4 shows the running rms amplitude jitter of 100 consecutive pulses σ_{KA} and σ_{KB}, measured by two identical PMS, labelled A and B, at 50 Hz repetition rate. For the whole period shown in Fig.3, the averaged jitter values are:

$$\overline{\sigma_{KA}} = 0.89 \text{ ppm}$$

$$\overline{\sigma_{KB}} = 0.91 \text{ ppm}$$

One way to reduce the noise contribution from the measurement system is to take the average of the two independent measurement systems for each pulse, KAB. The running rms amplitude jitter of 100 consecutive kicker pulses using the average from the two systems is denoted σ_{KAB} and the average value for this period is:

$$\overline{\sigma_{KAB}} = 0.72 \text{ ppm}$$

Using statistical analysis we can distinguish between the jitter coming from the kicker and from the two independent measurement systems.

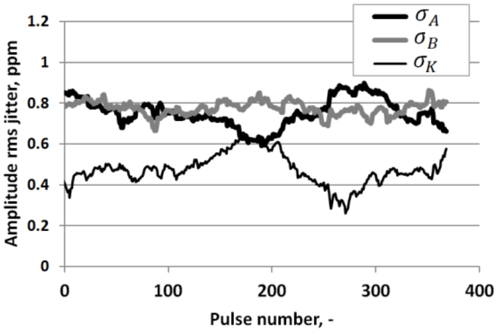

Figure 5: Statistically estimated noise floor and jitter of measurement system A, measurement system B and the kicker K.

Assuming that all correlated jitter in the two measurement series KA and KB comes from the kicker K and all uncorrelated one is due to measurement systems A and B (that is, the jitter of all three systems A, B and K is uncorrelated), then we can use Equations 1, 2 and 3 to estimate the amplitude jitter of the kicker σ_K and the jitter of the two measurement systems σ_A and σ_B [6].

$$\sigma_K^2 = 2\sigma_{KAB}^2 - \frac{\sigma_{KA}^2}{2} - \frac{\sigma_{KB}^2}{2} \tag{1}$$

$$\sigma_A^2 = \sigma_{KA}^2 - \sigma_K^2 \tag{2}$$

$$\sigma_B^2 = \sigma_{KB}^2 - \sigma_K^2 \tag{3}$$

Figure 5 shows the evaluated values of the running rms amplitude jitter for measurement system A, measurement system B and the Kicker. Respectively the averaged values for the shown period are as following:

$$\overline{\sigma_A} = 0.75 \text{ ppm}$$

$$\overline{\sigma_B} = 0.78 \text{ ppm}$$

$$\overline{\sigma_K} = 0.47 \text{ ppm}$$

PHASE NOISE CONTRIBUTION

Since the deflecting magnetic field follows the oscillating sinewave current of the kickers, beam deflection will depend on the relative bunch arrival phase as well. This arrival phase sensitivity is greatly reduced due to the fact that the electron bunches are deflected “on crest” where the derivative of the sine function changes sign. Using the measured kicker phase noise of 24 millidegree rms we can calculate the expected amplitude jitter due to phase noise σ_{PH} [6]:

$$\sigma_{PH} = 0.09 \text{ ppm}$$

This value is negligible with respect to the other jitter contributors.

CONCLUSION

A novel approach is used to separate closely spaced electron bunches using resonant kicker magnets. It relaxes the kicker driver requirements and makes possible to use entirely solid state driving technology.

Since the pulse-to-pulse stability is crucial for the overall system performance a lot of effort was focused on building a low noise floor measurement system capable of proving the kicker stability performance. As a result an offset based precision pulsed measurement system was designed and built with noise floor <1 ppm.

Using two independent measurement system and statistical analysis the reached pulse-to-pulse amplitude stability of the kicker is evaluated to be <0.5 ppm.

This result is well below the project requirements and should be capable of separating the two electron bunches with very little disturbance on the beam trajectory.

The success of this switching scheme together with the high amplitude stability opens possibilities to design more complex and demanding particle beam switching systems.

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