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MULTI-BEAMLINE OPERATION AT THE EUROPEAN XFEL

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Abstract

The European XFEL uses a unique beam distribution scheme to direct electron bunches to its three undulator lines. The accelerator delivers up to 600 microsecond long bunch trains, out of which parts or individual bunches can be selected for photon production in any of the FELs. This contribution gives a brief overview of the kicker-septum scheme facilitating this and highlights how even complex bunch patterns can easily be configured via the timing system.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) [1–3] delivers bursts of hard and soft X-ray laser pulses with an unprecedented average power to its experimental end stations. The facility is driven by a superconducting 17.5 GeV pulsed linear accelerator operating at a repetition rate of 10 Hz. Each pulse provides stable accelerating conditions for ~600 µs, which allows the transport of up to 2700 electron bunches at the maximum rate of 4.5 MHz. Distributing these bunches to the three undulator lines in a reliable and easily configurable way is challenging and requires the interoperation of multiple hard- and software systems. In this paper, we first give an overview of the involved systems before we focus on the high-level software for configuring the bunch distribution.

BEAM DISTRIBUTION SCHEME

The accelerator uses a unique beam distribution scheme to guide the electron bunches to its three undulator lines. This scheme is illustrated in Fig. 1: After the linac, a system of up to 10 in-vacuum stripline kickers [4] can generate pulses of ~30 ns width, which is short enough to selectively kick individual bunches to the left. A Lambertson septum [5] then deflects these bunches upwards into the transfer line to the linac dump (*TLD*).

The unkicked electrons continue straight to the next system of kickers, which consists of 6 air coils that are mounted on the outside of a ceramic vacuum chamber [6] and deflect upwards. With rise and fall times on the order of 10 µs, these *beam distribution* kickers are significantly slower than the previous set. This means that they provide better bunch-to-bunch stability, but they can only be used to influence an entire portion of the train, not individual bunches. Again, the kicked bunches are picked up by a Lambertson septum and deflected to the left and into the SASE2 undulator line which ends in the *T5D* dump.

Electrons that are influenced by neither kicker system take the straight path to SASE1 and SASE3 and finally end up in the *T4D* dump. A summary of the optics design for the beam distribution system can be found in [7].

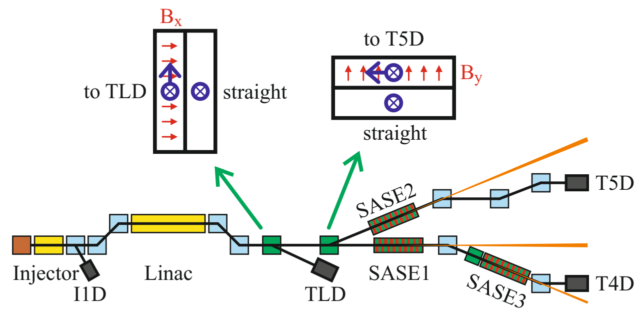

Figure 1: Schematic overview of the European XFEL. Accelerating structures are shown in orange and yellow, major bending magnets in blue, fast kicker systems in green, and beam dumps in dark gray. SASE1–3 are the undulator lines. The drawings above the beamline illustrate the operating direction of the magnetic Lambertson septa.

The photoinjector is driven by a single laser [8] that can produce a continuous train of pulses at 4.5 MHz, 1.1 MHz, or different rates. While the generated bunch train can be changed in length, it is currently not possible to leave gaps in it. Together with the characteristics of the two main kicker systems, this defines the boundary conditions for bunch distribution:

- From the gun up to the first *TLD* kicker, the beam forms a train of 0–2700 equidistant bunches.
- The *TLD* kickers can send an arbitrary number of the incoming bunches to the linac dump so that they never arrive in any undulator line. This can be decided individually for each bunch.
- Typically once per train the *distribution* kickers can change their state from on to off or vice versa so that a part of the remaining bunches is directed to SASE2 and the other part to SASE1/3. While these kickers are ramping, the incoming bunches must be sent to the linac dump by the *TLD* kickers.
- All of the settings above can be changed from pulse to pulse (i.e. at 10 Hz).

The common electron beamline shared by the SASE1 and SASE3 undulators adds another complication.

SASE1 and SASE3: Fresh Bunch Technique

Bunches destined for the hard X-ray undulator line SASE1 inevitably traverse the soft X-ray undulator line SASE3 and vice versa. This poses a serious problem for the concurrent

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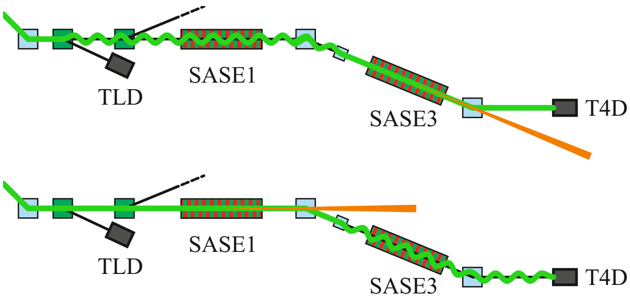

Figure 2: Illustration of the fresh bunch technique. *Top:* Bunches destined for lasing in SASE3 are deflected by one of the TLD kickers so that they oscillate through SASE1; afterwards, an orbit correction brings them onto a straight trajectory through SASE3. *Bottom:* Bunches destined for lasing in SASE1 receive no kick and therefore follow a straight trajectory in SASE1 and oscillate through SASE3.

usage of both beamlines: If bunches are lasing in SASE1, they typically gather enough energy spread to make them unusable in SASE3.

The *fresh bunch technique* as illustrated in Fig. 2 is a way of decoupling the beamlines: One of the fast *TLD* kickers can be triggered separately from the others. When activated, it imparts only a small angular deflection – a *soft kick* – to bunches that are selected for lasing in SASE3. This causes them to perform a betatron oscillation in SASE1 and suppresses the FEL process there. A static orbit correction in front of SASE3 brings these bunches back to a straight trajectory so that they start lasing in the soft X-ray beamline instead. Conversely, bunches destined for lasing in SASE1 receive no kick, follow a straight trajectory through the undulator and produce hard X-rays. The static orbit correction in front of SASE3 makes sure that these bunches follow an oscillating trajectory until they reach the dump, suppressing the FEL process in the soft X-ray beamline. More information on the operation of the facility in this mode is found in [9].

TIMING SYSTEM

The timing system [10, 11] describes each bunch train by an array of 7200 *timing words*, i.e. 32-bit integer numbers. This corresponds to one entry for each 9-MHz sampling point along a time span of 800 µs, starting just after the filling time of the radiofrequency cavities. Each number in this *timing pattern* describes what should happen in the corresponding time slot. As shown in Fig. 3, the timing word contains individual bits that determine which kickers, injector- and user lasers should be triggered. It also carries encoded information about the maximum charge and about the destination beam dump of each bunch. With each new 10-Hz pulse of the accelerator, a new timing pattern can be defined in software.

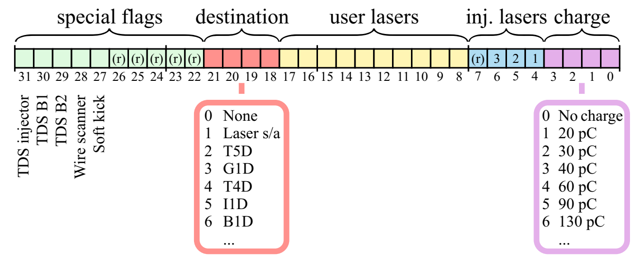

Figure 3: The 32-bit timing word encodes the destination and the maximum charge for a bunch as well as information for various subsystems.

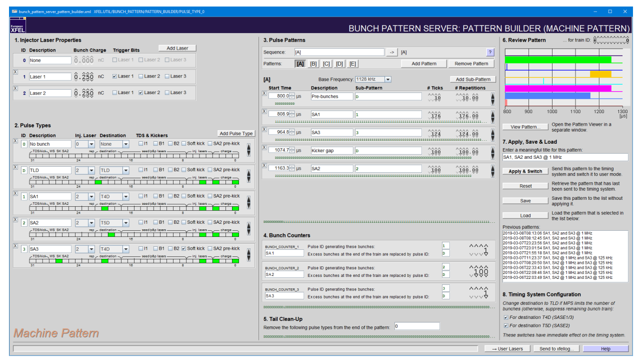

Figure 4: Screenshot of the user interface for configuring timing patterns.

DEFINING BUNCH PATTERNS

The machine operators use a high-level software, the *bunch pattern server*, to set up the timing patterns for the machine. Figure 4 shows a screenshot of the user interface, which is configured and operated with the jddd [12] user interface builder.

Pulse Types

Pulse types are the building blocks for a timing pattern. Each pulse type consists of a freely configurable 32-bit timing word (which defines the bunch destination and other characteristics) and an identifying character. Typical pulse types are:

0 An empty timing word – no bunch and no special triggers.
1 A bunch lasing in SASE1 (no soft kick).
2 A bunch lasing in SASE2.
3 A bunch lasing in SASE3 (with soft kick).
D A bunch that is dumped after the linac.

Any number of pulse types can be defined.

Pulse Patterns

The pulse types, identified by their corresponding characters, are grouped into *subpatterns* that can be repeated any number of times. Multiple subpatterns are then concatenated to define a full pattern. To give an example, a bunch pattern used during photon delivery might consist of:

D × 100 one hundred *pre-bunches* that give fast beam-based feedbacks enough time to stabilize the beam parameters and are discarded after the linac,

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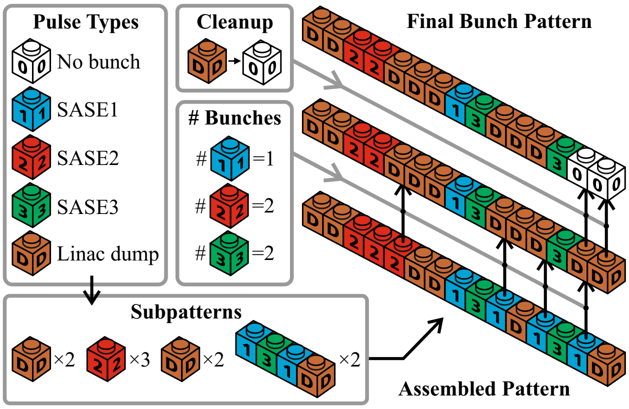

Figure 5: Illustration of the main steps for building a bunch pattern.

2 × 200 two hundred consecutive bunches for SASE2,

D × 120 one hundred and twenty bunches that are dumped during the falling edge of the beam distribution kicker,

131D × 140 one hundred and forty times the interleaved sequence "one bunch to SASE1, one to SASE3, one to SASE1, one to the linac dump".

As laid out earlier, the native frequency of the timing pattern is 9 MHz. To simplify the definition of patterns for the typically used 4.5 MHz, 2.2 MHz (as in the example above), 1.1 MHz or even lower frequencies, the base frequency for the pattern can be selected. The effect is equivalent to inserting empty timing words (**0**) between the ones defined in the pattern.

Controlling the Number of Bunches

A pattern defines the maximum number of bunches that are available for each beamline in a single macropulse – in the example, 200 for SASE2, 280 for SASE1, and 140 for SASE3. Both the operators and the beamlines can reduce the number of bunches for a specific beamline through a simple substitution mechanism: If N bunches for SASE1 are desired, only the first N occurrences of **1** in the pattern are retained whereas all of the following ones are replaced by **D**, which means that these bunches are sent to the linac dump instead. Of course, also this mechanism is fully configurable. If desired, an additional *cleanup* step can automatically truncate unnecessary bunches from the end of the train (e.g. bunches that would only be accelerated to be discarded after the linac). Figure 5 illustrates the way bunch patterns are composed.

Adding Rhythm: Pattern Sequences

The mechanisms outlined above provide a multitude of ways for sharing the bunch train between the three beamlines. Sometimes, however, even more flexibility is required. The coexistence of SASE1 and SASE3 on the same electron beamline implies that the experiments observe spontaneous radiation from the bunches that are destined for the other beamline. This background is greatly reduced through collimation and can in most cases be ignored, but for a few experiments it may nevertheless become intolerable. Mechanical choppers or similar slow methods for background suppression can help, but they require a bigger temporal separation of FEL pulses and unwanted radiation. For these cases, we added the option to change the bunch pattern from macropulse to macropulse.

Up to 10 bunch patterns can be defined under the symbols `[A]` to `[J]`, and a *pattern sequence* specifies the order in which they are applied to the machine. These sequences are always repeated periodically, but can be of arbitrary length and complexity. For instance, we might define a pattern `[A]` which only contains bunches for SASE1 and a pattern `[B]` with bunches for SASE3 and then define a sequence of "`[A] 4[B]`". This would deliver pattern `[A]` on every 5th macropulse, followed by 4 shots with pattern `[B]`. Schemes like this have already found application during user operation.

CONCLUSION AND OUTLOOK

The European XFEL uses a unique beam distribution system to divide its electron bunches among the three undulator lines. The pulsed operation mode and the necessity of beam dynamical schemes such as the *fresh bunch technique* to allow the coexistence of two FELs on the same electron beamline generate extraordinary challenges – not only for hard- and software, but also for the people involved in the operation of the facility.

The flexible configuration of bunch patterns for the machine allows us to cater to the specific needs of our photon experiments. Although the system is capable of generating enormously complex patterns, the chosen abstractions make it manageable for all our operators.

In the future, we are going to add one or more undulator lines in the SASE2 branch. We are also going to commission a set of fast kickers in front of the SASE3 undulators to selectively increase the amplitude of the orbit oscillation that suppresses radiation from passing SASE1 bunches. Both projects can easily be realized with the current timing hard- and software.

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