HIGH LEVEL SOFTWARE FOR THE COMMISSIONING OF THE EUROPEAN XFEL

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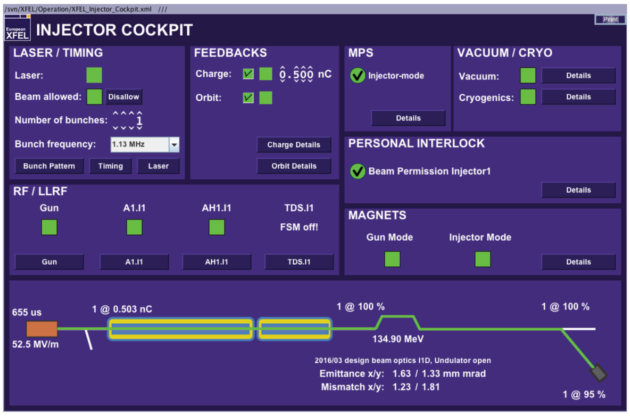
Abstract

The European X-Ray Free-Electron Laser (XFEL) will generate extremely short and intense X-ray flashes from the electron beam of a 2.1 km long superconducting linear accelerator. The commissioning and operation of the accelerator relies heavily on high level software for the automatization of measurements and procedures. The paper gives an overview of the ongoing work and highlights some new measurement techniques.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) is a research facility that has been constructed in collaboration between the European XFEL Facility GmbH[1] and DESY[2] in Hamburg, Germany [1–4]. The main component of the facility is a superconducting linear accelerator (linac) that delivers an electron beam with particle energies up to 17.5 GeV and average beam power up to ~600 kW into several long undulator sections. In these sections, the electrons generate extremely brilliant X-ray pulses at wavelengths down to 0.05 nm. These light pulses are distributed to several beamlines and end-stations for photon science experiments. Extensive infrastructure, including a cryogenic plant, has to be operated to allow the XFEL to work. An overview of the control system architecture for the entire facility is given in [5]. The 130 MeV injector has already been fully commissioned with beam, and the commissioning of the entire machine will start soon.

The XFEL is a system of considerable complexity, and operating it smoothly requires a high degree of automatization. We therefore aim to offer high level abstractions for all important machine parameters and to develop user friendly tools for typical physical and technical tasks in the control room. This paper gives a brief overview of our evolving control system landscape, reports on our experience from the commissioning of the injector, and highlights a few applications that have enabled us to perform unprecedented measurements of the beam emittance across the bunch train with a new measurement techniques.


/svn/XFEL/Operation/XFEL_Injector_Cockpit.xml ///

INJECTOR COCKPIT

LASER / TIMING
Laser: 🟩
Beam allowed: 🟩
Number of bunches: 1
Bunch frequency: 1.13 MHz

FEEDBACKS
Charge: ☑ 🟩 0.500 nC
Orbit: ☑ 🟩

MPS
✓ Injector-mode

VACUUM / CRYO
Vacuum: 🟩
Cryogenics: 🟩

PERSONAL INTERLOCK
✓ Beam Permission Injector1

RF / LLRF
Gun 🟩
A1.I1 🟩
AH1.I1 🟩
TDS.I1 FSM off!

MAGNETS
Gun Mode 🟩
Injector Mode 🟩

655 us
52.5 MV/m
1 @ 0.503 nC
1 @ 100 %
134.90 MeV
1 @ 100 %
2016/03 design beam optics I1D, Undulator open
Emittance x/y: 1.63 / 1.33 mm mrad
Mismatch x/y: 1.23 / 1.81
1 @ 95 %

Figure 1: Screenshot of the “injector cockpit” *jddd* panel.

FUNDAMENTALS

No less than four main control system protocols are in use at the XFEL: DOOCS [6, 7], EPICS [8, 9], TINE [10, 11], and Karabo [12]. A lot of work has already been invested to improve the interoperability of the first three protocols [13], so that the problem of network communication across protocol boundaries is less daunting today than it was several years ago. Most of the remaining cross-protocol effort is focused on creating an interface with Karabo.

We are operating a central *configuration database* as a network service. It stores a complete list of beamline components and associated information such as calibration data. This helps to avoid inconsistencies in the configuration of distributed servers [14].

In large parts, XFEL controls follow a “rich server–thin client” philosophy. We are trying to implement high level abstractions and advanced data processing at the server level so that many user interfaces do not need to be programmed but can be configured with our *jddd* [15, 16] user interface builder (Fig. 1). Even applications requiring more complex interaction or more advanced plotting capabilities become simpler to write and easier to maintain with this approach.

Almost all of the control system servers for the machine are written in C++ and deployed on Linux systems. We have created a multitude of libraries to facilitate easy access to various accelerator components and to the central database, for numerical and image analysis tasks, for the calculation of optical functions, and for particle tracking. GUI applications are deployed on MacOS, Windows, and Linux desktops and written in Matlab, Java, or Python. Toolboxes and libraries for these languages are available as well.

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VIRTUAL XFEL

Before installation in the real machine, many control system components of the XFEL can be tested in the *Virtual XFEL*, a deep simulation of the accelerator that runs on dedicated hardware with its own separate timing system [17]. Beam positions, charge readings, magnet currents, and other data are generated by fake front-end servers and passed to the original middle layer and data acquisition software for processing. A physics simulation performs particle tracking in real time based on the setting of the virtual magnets and feeds the beam positions back to the fake front-end servers, closing the loop. The result is a virtual machine that feels almost like a real one—beam cannot be transported properly until a reasonable magnet file has been loaded, changes in beam energy reveal spurious dispersion. We are continually improving the simulation in order to provide a test bed even for complex beam dynamics tasks such as beam-based undulator alignment.

INJECTOR COMMISSIONING EXPERIENCE

From December 2015 to July 2016, we commissioned the injector of the European XFEL with beam. Although it is only ~50 m long, it contains almost all of the subsystems of the entire machine—most notably (Fig. 2): an RF gun, a small spectrometer for the 5–6 MeV beam, one cryomodule with eight accelerating 1.3 GHz cavities (A1), one cryomodule with eight decelerating 3.9 GHz cavities (AH1), a laser heater chicane with a small undulator, an optics matching and diagnostic section with a transverse deflecting RF structure (TDS), four fast kickers and four scintillation screens, and a dump line to safely dispose of the 130 MeV electron beam.

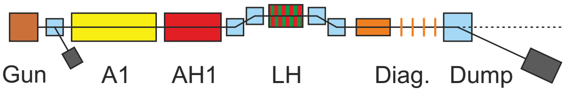

Figure 2: Schematic of the XFEL injector.

The commissioning relied heavily on high level software from the very start. For example, a middle layer server allowed controlling magnets by physical parameters such as deflection angles, fields, and particle energies instead of setting currents directly [14], and trajectory, transmission, and beam loss displays used pre-processed data from the data acquisition system (DAQ). The startup, conditioning, recovery, and shutdown of the RF stations was handled by finite state machines implemented as middle layer servers. Support for finding the optimal phase of the RF wave in the gun and in the cryomodules was also available through middle layer servers and standalone tools from the very beginning.

A number of generic multi-purpose utilities proved extremely useful for the commissioning of technical systems and for the automation of common tasks and measurements. These include tools for data recording, scans of arbitrary control system channels, and correlation finding, as well as utilities for performing configurable checks on subsystems and for executing sequences of control system commands.

Beam-based feedbacks for bunch charge and trajectory could be tested soon after the commissioning of the standard diagnostics systems of the injector. They are based on the same architecture as the ones used at FLASH [18].

A good knowledge of the beam energy is essential for having control of the beam optics. From the very start, we could rely on the setting of the gun and the injector dump dipole for energy measurements. Later on, we commissioned a multi-layered system of energy information servers that provides the best possible energy information for the entire machine:

- A *LLRF energy gain server* gathers the expected energy gain for each RF module in the linac, taking acceleration phases and the possible disabling of modules into account.
- One or more *beam energy measurement servers* perform beam-based energy measurements in dispersive sections of the machine. This already worked well in the laser heater chicane and will be set up in many more places along the accelerator.
- An *energy profile server* scales the data from the LLRF energy gain server to the measured energies, providing a consistent energy profile for the entire machine in realtime.

Of course, there is also tool support for adjusting the magnetic lattice to this energy profile with few mouse clicks.

An *Elegant* [19]-based optics server [20] with a complete optics model of the machine provided a powerful engine for optics calculations as a network service from day one. It was later extended with matching capabilities and now serves as the backbone of most software related with beam optics. As an example, a simple *orbit response tool* proved most helpful for the cross-validation between the optics model and the actual magnetic lattice. By measuring the response of beam positions to the variation of corrector strengths, polarization errors and swapped planes can easily be diagnosed. In addition, the same tool can be used to determine the offset of quadrupoles by varying their strength, and measure dispersion by varying the beam energy.

EMITTANCE MEASUREMENTS AND OPTICS MATCHING

The beam exiting the RF gun is subject to strong space charge forces and eludes modelling in the usual framework of linear optics. Therefore, we follow the standard approach for linacs and match the beam to a design optics only after acceleration to ultrarelativistic energies in A1 and AH1, where linar optics can be used again. In order to perform this *matching*, the Twiss parameters (α, β, γ, and the emittance ε) of the beam need to be measured first. Because good control of the beam optics is essential for a smooth operation of the machine and because the emittance is an eminently important parameter for the FEL process itself, we have

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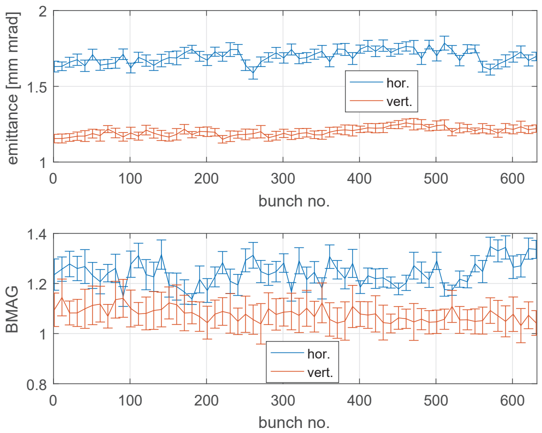

Figure 3: Normalized projected emittance and mismatch amplitude (BMAG) along the bunch train.

invested a lot of work into several independent measurement methods:

- The *four-screen on-axis* method acquires beam images from four scintillation screens with a fixed betatron phase advance between them. These four screens intercept the beam in its normal path, and have to be inserted and removed one by one to obtain images. The method is very robust and produces a measurement of the projected emittance in about three minutes.
- The *four-screen off-axis* method is similar, but faster: The screens are only inserted half-way into the beam pipe, so that they do not intercept the normal bunch train. Four fast kicker magnets are then fired to deflect individual bunches onto these off-axis screens. An emittance can thus be measured in few seconds and without interrupting the normal operation of the accelerator.
- The *quadrupole scan* method uses only a single screen and changes the phase advance by varying the strength of an upstream quadrupole. Because of its versatility, this method provides a good way of cross-checking the results of the other tools in multiple locations. We use an adapted version of the tool from the FERMI FEL. The method can also be extended into a multi-quadrupole scan that varies several magnets simultaneously to achieve better resolution; we have used this approach to good effect, but have yet to implement it in a non-expert tool.

The setup with kickers and off-axis screens allows us to measure emittances frequently. Automated measurements in intervals of few minutes could easily be implemented to monitor drifts of the beam optics over time. The kicker setup also made it possible for the first time to examine the evolution of the emittance over an entire bunch train; Figure 3 shows the horizontal and vertical emittance over a train of 650 bunches along with the mismatch amplitude (BMAG) with respect to the design optics. The method also integrates well with the use of the transverse deflecting cavity—by streaking individual bunches, slice emittances can easily be measured (Fig. 4), and individual slices can be matched to a target optics.

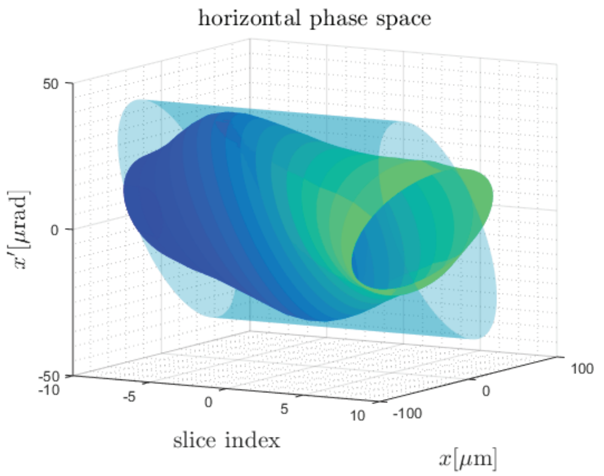

Figure 4: Horizontal phase space of the beam, measured with the four-screen off-axis method and transverse deflecting cavity.

CONCLUSION AND OUTLOOK

The European XFEL is a machine of considerable complexity, not only due to its sheer size and number of individual components, but also because of the intricacies of its pulsed mode of operation, of its beam distribution system, and of many subsystems. We are trying to reduce this complexity by offering more high-level, physical abstractions for all important machine parameters directly in the control system. This effort goes hand in hand with the development of user friendly tools for typical tasks in the control room.

Our experience with high level controls during the commissioning of the XFEL injector was generally a very positive one. The early availability of middle layer servers for optics calculations, magnet parameters, beam energies etc. made many commissioning tasks easier than expected. Based on this foundation, several measurement algorithms for emittances (both projected and slice) and Twiss functions could be developed and cross-checked successfully, which are now in the standard toolbox of every machine operator. This has given us an unprecedented amount of control over the injector optics—down to the matching of individual slices. We are now looking forward to the commissioning of the entire linac in the near future.

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