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RF COMMISSIONING AND FIRST BEAM OPERATION OF THE POLARIX TRANSVERSE DEFLECTING STRUCTURES IN THE FLASH2 BEAMLINE

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Abstract

In January 2021 two X-band (12 GHz) PolariX Transverse Deflecting Structures with variable streak polarization were installed into the FLASH2 beamline at FLASH. Since none of the RF components for the FLASH2-PolariX RF-distribution system nor the two PolariX structures could be pre-conditioned, RF-conditioning was and is quite tedious. Nevertheless, after 6 weeks of conditioning, we have already been able to streak the electron beam enough to start commissioning of the PolariX controls and the software. After 4 months of conditioning in parallel to FLASH2 user operation, we achieved a stable 5.5 MW flat top of 400 ns operation. Next step will be to include RF pulse compression to achieve the design power of 22 MW.

INTRODUCTION

FLASH [1–5] at DESY (Hamburg, Germany) is a free-electron laser (FEL) user facility. FLASH consists of a normal-conducting photo-injector, and a superconducting linac. The superconducting LINAC can accelerate several thousand electron bunches per second in 10 Hz bursts of up to 800 µs length. The long bunch trains are split in two parts and are shared between two undulator beamlines. FEL radiation can be generated with the SASE (Self Amplified Spontaneous Emission) process and fundamental wavelengths ranging from 4 nm to 90 nm. In addition, FLASH hosts a seeding experiment Xseed [6], and a plasma wakefield acceleration experiment FLASHForward [7]. In order to keep FLASH a state-of-the-art FEL user facility, an upgrade project "FLASH2020+" is on-going [8–10], which includes an upgrade of the longitudinal diagnostics. Optimizing the performance of an FEL requires a precise knowledge of the longitudinal phase space distribution of the bunch. Transverse deflecting structures (TDSs) enable high resolution, direct measurement methods to determine the longitudinal properties of the bunch and allow to measure transverse-to-longitudinal correlations (centroid shift, mismatch, emittance, etc.) in the plane perpendicular to the streaking plane. The RF structures support an Eigenmode with a transverse electric field component, thereby deflecting electrons within the bunch transversely depending on the arrival time in respect to the RF wave. High amplitudes of the electric field and high RF frequency both improve the resolution. A collaboration between CERN, PSI and DESY has been established to develop and build an advanced modular X-band TDS [11, 12]. The PolariX is an X-band (12 GHz) TDS with the new feature that the polarization of the transverse electric field can be varied by tuning the phase difference between two perpendicular in-coupling ports of the structure. This allows the measurement of the longitudinal distribution of emittance and mismatch in both transverse planes and even, to some extent, phase space tomography [13].

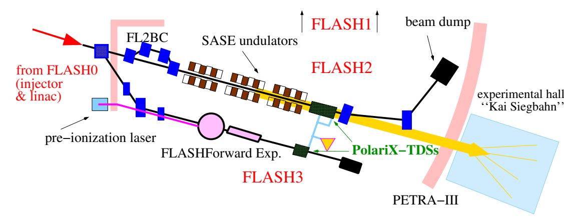

Figure 1: Schematical view of the FLASH2/3 beamlines with the 2+1 PolariXes and the shared X-band RF transmitter. Not to scale.

The prototype PolariX structure was installed in an optimized diagnostic section of the FLASHForward experiment in 2020 [14]. The prototype was pre-conditioned at CERN and some RF equipment could be pre-conditioned at a test assembly of klystron and modulator at DESY. In the winter shutdown 2020/2021 a system of two short (0.8 m long) PolariX-structures was installed in FLASH2 [15, 16]. Figure 1 gives a schematic overview of the layout of the FLASH2/3 beamlines and the installed PolariX system. In FLASH2 the RF structures were installed 2.0 m downstream of the end of the last SASE undulator and 2.40 m upstream, of the 3.5°-dipole separating the electron beam from FEL beam[1]. Any single bunch in the standard 1 µs timing pattern can be kicked onto a screen located 5.5 m downstream of the separator dipole. Immediately downstream of the PolariX section the beam of potentially several thousand bunches per second and a maximum beam power of 100 kW has to be prepared to be safely dumped. This set up is not optimal since there is not enough space for many quadrupoles *and* sufficient phase advance between them to achieve the wanted high temporal and energy- resolution with the streak from only one standard PolariX structure. However, with two PolariXes and a carefully designed beam optics this set up allows to measure the shape of the complete longitudinal bunch phase space distribution with temporal resolutions in the sub-10 fs range and supplies sufficient energy resolution

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[1] Positions refer to *center* positions unless otherwise noted.

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to determine the fraction of the bunch that participated in the FEL process.

FLASH2 and FLASHforward share the same tunnel, and the corresponding PolariXes were located close to each other. Thus, it was decided to use a common RF driver system for both PolariX diagnostic stations. The structures are driven by a 6 MW Toshiba klystron E37113A operated at a frequency of 11.988 GHz. The klystron is located in the tunnel in between the PolariX sections of FLASH2 and FLASHForward. The required HV pulses are generated by an Ampegon Type-μ M-class modulator which is located in a service isle outside the tunnel. To generate more streaking voltage for FLASH2, an RF pulse compressor (X-BOC, X-band barrel open cavity [17]) was installed at the output port of the klystron during the winter shutdown 2020/2021.

A remote-controlled waveguide switch is used to switch the RF power between the FLASHForward PolariX and the two FLASH2 PolariXes. Ceramic windows isolate the vacuum in the waveguide distribution system from the beam vacuum systems in FLASH2 and FLASHForward. The FLASH2 system first splits the power between the two PolariX units. A phase shifter with a range of 0° to 200° is placed before one of the PolariXes to compensate unavoidable phase differences between the two structures.

RF CONDITIONING

Conditioning of the FLASH2 PolariX TDS system started quickly after the installation in the FLASH2 beamline. The two structures, the X-BOC, the phase shifters, and all the new waveguide components could not be pre-conditioned prior to the installation. Since the RF controls for generating a well-behaved RF pulse at the output of the X-BOC were not fully functional, we started conditioning with the X-BOC thermally detuned by about 25 25 K. So far, stable operation has been achieved at a power level of 6 MW for 400 ns, equivalent to what has been achieved at the FLASHForward PolariX. We did not reach the design performance, but achieved sufficient power to perform phase space mappings with an already very good resolution below 10 fs with a moderate optics suitable for multi-bunch mode (see below). The conditioning will resume after restarting FLASH from the 9 month 2021/22 shutdown [5]. In particular we plan to quickly move to condition the system with activated X-BOC.

PolariX COMMISSIONING

The complex transverse (time-independent) field-amplitudes, streaking ($\hat{E}_s := E_{x,s} + iE_{y,s}$), and kicking ($\hat{E}_k := E_{x,k} + iE_{y,k}$) the bunch which traverses the compound system of two PolariXes can be parameterized as follows.

$$\begin{aligned} \hat{E}_s &= \;\; A\left(\exp(i\psi_1) + \exp(i\psi_2)\cos(\psi_{12})\right)\cos(\phi_{\mathrm{RF}}) \\ \hat{E}_k &= -A\left(\exp(i\psi_1) + \exp(i\psi_2)\sin(\psi_{12})\right)\sin(\phi_{\mathrm{RF}}) \;, \end{aligned}$$

where $A := \sqrt{R_s P_{\mathrm{fwd}}/4}$ is the (real) amplitude due to the forward power after twice splitting with 3 dB per arm, ψ_1 and ψ_2 are the phase differences between the horizontal and the vertical port of structure 1 and structure 2 respectively, ψ_{12} is the phase difference of beam-to-RF between structure 1 and 2, and ϕ_{RF} is the common RF phase from the klystron input drive amplifier and controller. The phases depend on the position of the corresponding three phase shifters (control knobs) as well as on path differences of the waveguide distribution system between the corresponding ports — and thus *all* have to be adjusted empirically. The problem is that the two PolariXes cannot be operated alternatively but only in parallel (behind the 1st 3 dB splitter). The set-up is such that one may expect that ψ_1 and ψ_2 come out similar for parallel streak amplitude in both structures. Under the assumption that interference of the phase shifters is weak, one may maximize the streak (minimize the kick), and fix the polarization direction, by iteration of tuning the various knobs one-by-one. In fact, tuning and calibrating the phase shifters took about one shift(8 h).

When setting up a TDS for a measurement, its effective streak, i.e. the mapping of longitudinal distance inside the bunch to observed transverse distance on the screen must be calibrated. This is usually done by varying ϕ_{RF} and correlate it with the bunch centroid position on the screen. The RF-coupling of the PolariX system to the FLASH master timing was initially done in a way that included a lot of ambient jitter and phase drifts. Thus that the above phase scans had to be optimized for scanning time rather than sample size. However, we have developed a suite of tools that perform the streak calibration, take and evaluate calibrated picture. Furthermore the RF-coupling of the system will be improved in the next long shutdown 2024/25. The default streak orientation is vertical, since the dispersion from the electron/photon separation which is used for the energy measurement is in the horizontal plane. Since the complete FLASH sub-train always has to pass this dispersion section, we are able to perform online bunch length measurements *and* can map the complete longitudinal phase space on an off-axis screen for an arbitrarily kicked bunch out of the sub-train. The energy resolution can unfortunately not be well calibrated in non-destructive mode due to aperture limitation for the off-axis screen. In destructive (single bunch) mode the energy resolution can be calibrated with improved accuracy. First preliminary scans of the vertical slice emittance have been successfully performed using a horizontal streak and a vertical quadrupole scan on the screen. We have developed a technique to compensate the unavoidable horizontal dispersion in a horizontal quadrupole scan, but could not yet spend enough time on this method to obtain useful results before the machine went into the ongoing shutdown last November.

USER OPERATION

Since mid-2021 we routinely use PolariX for tuning compression for FLASH2 i.p. for user experiments requesting short FEL pulses. In addition, we offer dedicated PolariX measurements to users who need pulse length estimates for evaluating their experiment. So far, we did not offer continuous PolariX bunch length monitoring because of

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electromagnetic interference between the PolariX system (RF, and/or kicker) and certain photon diagnostics and because of insufficient radiation shielding between the PolariX screen and certain photon diagnostics. This last problem is under survey and we are planning to improve the shielding on one or the other side. Figure 2 shows two bunches which

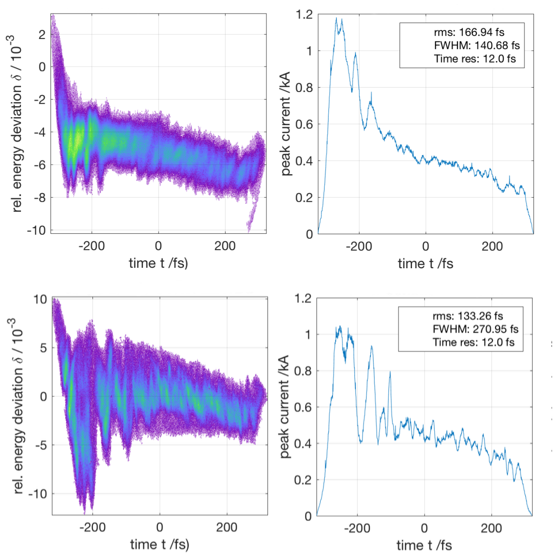

Figure 2: Two bunches of the same beam set up: Top row with open undulators. Bottom row with closed undulators.

have been set up almost identically except that one (top row) was measured with open undulators while the other (bottom row) was measured with closed undulators and a single pulse SASE energy of 250 µJ at 21 nm. One observes the enhanced energy spread and the reduced centroid energy in the head of the bunch (to the left). This indicates the region of active FEL lasing and therefore gives an estimate on the photon pulse length. Figure 3 shows a bunch prepared

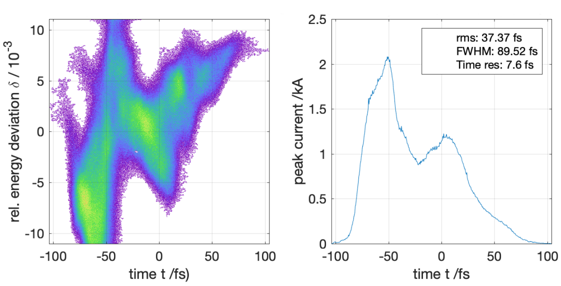

Figure 3: Bunch prepared for short pulse operation for a user experiment.

for user operation with short pulses. Note the very good temporal resolution below 8 fs.

MACHINE STUDIES

Since PolariX at FLASH is operational (with reduced power), many FEL and accelerator studies included dedicated and "service"- PolariX measurements. In particular we had a campaign on studying micro bunch effects with several lattice and compression variants in FLASH1 (with LOLA [18]), and in FLASH2 (with PolariX). This study is still being evaluated and will be reported elsewhere. Figure 4 is an exotic example of a heavily micro-bunched bunch observed during the dedicated micro-bunching studies. In

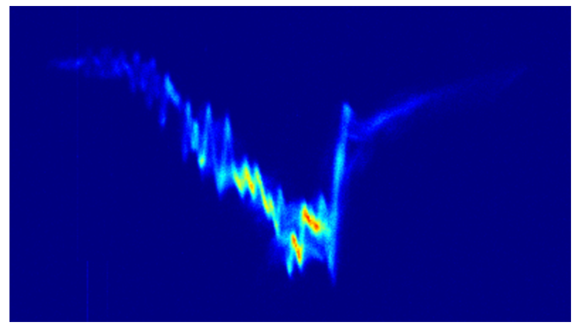

Figure 4: Heavily micro-bunched bunch prepared for accelerator studies.

addition we have complemented the THz photon pulse streaking studies [19] with PolariX measurements with closed and opened FLASH2 undulators. The evaluation of the lasing bunch region using PolariX images with open and closed undulators still needs a lot of manual, intervention, i.e. by-eye interpretation of PolariX phase space mappings with and without FEL process. Nota bene: one can *never* compare images of the *same* bunch with and without lasing! A project has been started [20] to employ machine learning to evaluate the images.

CONCLUSION & OUTLOOK

Two PolariX TDSes have been installed in FLASH2. The initial RF conditioning and the PolariX commissioning was very successful. We routinely use PolariX at FLASH2 for tuning for users and machine studies. We are looking forward to continuing our efforts after recommissioning FLASH after the 1st long FLASH2020+ shutdown in September.

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