EXPERIENCE WITH SHORT-PERIOD, SMALL GAP UNDULATORS AT THE SwissFEL ARAMIS BEAMLINE

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Abstract

The SwissFEL Aramis beamline provides hard X-ray FEL radiation down to 1 Angström with 5.8 GeV and short period, 15mm, in-vacuum undulators (U15). To reach the maximum designed K-value of 1.8 the U15s have to be operated with vacuum gaps down to 3.0 mm. The thirteen-undulator modules are 4m long and each of them is equipped with a pair of permanent magnet quadrupoles at the two ends, aligned magnetically to the undulator axis. Optical systems and dedicated photon diagnostics are used to check the alignment and improve the K-value calibration. In this talk the main steps of the undulator commissioning will be recalled and a systematic comparison between the magnetic results and the electron and photon based measurements will be reported to highlight achievements and open issues.

INTRODUCTION

The hard x-ray Aramis beamline of SwissFEL started operation with first lasing end of 2016, but only in the soft x-ray at 400 eV. This was caused by a delay with the newly developed solid state rf modulators. During 2018, the energy could be successively increased until the full energy with 6 GeV has been reached end of 2018. In March 2018, the working range of the monochromator has been reached, so that a first photon based alignment campaign could be done. Because of the short period length of 15 mm, only 13 undulator modules with 265 periods in 4 m length each are needed for lasing down to 1 Å, as shown in Fig. 1. The gain length is typically between 2 and 3 m, so that every undulator causes a significant increase in power. The undulators are placed on remotely controlled 5-axis cam-shaft mover which allow horizontal and vertical positioning and all 3 angles with µm precision. The mover have a range of up to 3 mm, but are limited by the bellow transverse motion of only 0.5 mm. For the planar U15, height and pitch alignment are the most relevant, but the original design strategy was to use the same support units also for the soft x-ray undulators of APPLE type where in addition horizontal position and yaw angle are of equal importance.

The main issue of the Aramis beamline, like for all the others, is to get the orbit straight at the tolerances of an hard X-ray FEL, align the undulators to this orbit and set the correct *K* - values and phase matching between two successive undulators. For this reason, the first step in setting up the Aramis beamline is the beam based alignment (BBA). While not needed for the commissioning of the fixed gap LCLS, the photon based undulator alignment was essential for the commissioning of SACLA [1]. The strategies for photon based alignment and optimisation have been adapted for SwissFEL, which, however, could start lasing with lower electron energies at longer wavelengths and could successively improve the alignment.

Figure 1: SwissFEL hard x-ray Undulator Aramis.

The magnetic field data taken during the magnetic optimisation and characterisation of the undulators in the undulator laboratory are prepared with a bundle of models including the gaps, the corrector settings and the correct phase shifter settings which has been named SUBLIME (aramiS Undulator BeamLIne ModEl) [2], see Fig. 2.

In the following, the setup for the alignment of the undulators is discussed with a focus on the photon based diagnostic

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on spontaneous synchrotron radiation. The results of two optimisation campaigns will be reported, followed by some examples of the undulator related FEL performance.

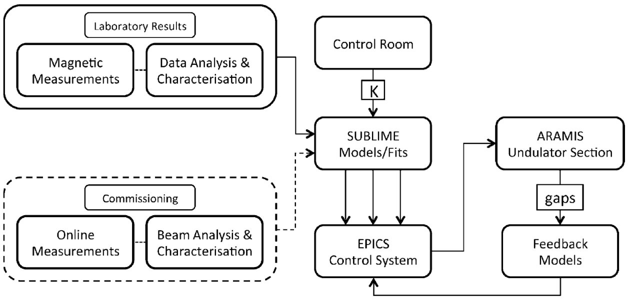


Figure 2: Schematic for the Aramis beamline operation: Magnetic data from the Hall-probe based measurements are fine corrected with photon based commissioning data. The corresponding phase-matcher settings as well as corrector settings from the ends of each undulator and the the distributed earth field correction coil are implemented in feed forward mode.

STRAIGHT ELECTRON ORBIT

The pre-condition for a good undulator optimisation is a straight, dispersion-free electron beam orbit through the entire undulator line. At Aramis, different concepts of BBA including a general otimiser tool (PSICO) have been tested: random walk concepts and more recently dispersion free steering [3], which gives the best orbit with zero dispersion in the undulator. Moreover, this *golden orbit* has to be matched with the ideal photon beam axis which is required to pass all optical elements further down the beamline to the sample positions in the endstations. The PSICO optimiser works with the FEL signal and is made for the final tuning on a day to day basis. Undulator related errors are also often caused in orbit errors which can be based i.e in mismatch of the machine optics or dispersion in the undulator. The error source is often not obvious.

All undulators were already installed before the commissioning could start. The undulators can be opened, but not so much that the field and errors in first and second field integrals which causes kicks and offsets are zero. But, of course, all the corrector settings found during the magnetic measurements of the undulators are implemented.

UNDULATOR PRE-ALIGNMENT

The undulators are equipped with a small fixed gap permanent magnet quadrupole at the entrance and exit of each undulator. At the end of the magnetic measurements in the laboratory these alignment quadrupoles (QA) were aligned to the magnetic axis. For this, the Hall probe is positioned at the position of the quadrupoles and with a mechanical flexor system the quadrupoles were aligned to give zero field on axis. A pneumatic system can remotely bring the quadrupoles in and out. The accuracy and reproducibility is about 10 µm. These alignment quadrupoles are designed to allow an alignment to the electron beam axis, using a beam based alignment algorithm. For that, first the upstream quadrupole will be brought on axis. As the electron beam gets a kick when it goes off-axis through the quadrupole, the center of this quadrupole - and with that the magnetic axis of the undulator - can be detected. The cam-shaft mover settings are corrected remotely and the up-stream QA is extracted from the beam axis. The procedure is repeated with the downstream side of the undulator.

This procedure has a better precision than the laser tracker based installation which has a precision of only 100 µm and, more important, this refers the magnetic axis directly to the beam orbit.

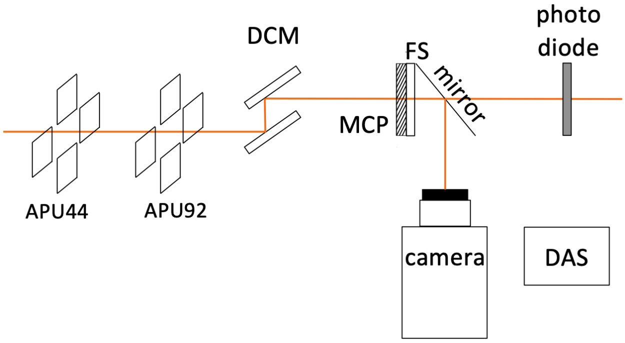


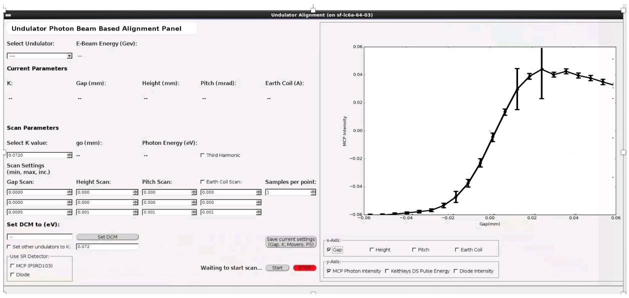
Figure 3: Setup for the photonics instrumentation: the spontaneous radiation cone is shaped with two 2-dim slit units APU, filtered by a double crystal monochromator (DCM) and detected by either a multi channel plate (MCP) for 2-dim pictures or a photodiode for intensity information.

INSTRUMENTATION FOR PHOTON BASED ALIGNMENT

The setup for undulator characterisation using spontaneous undulator radiation is shown in Fig. 3. After a double crystal monochromator two systems are installed for spontaneous synchrotron radiation characterisation. To measure the intensity of the spontaneous synchrotron radiation for alignment and gap scan measurements a Si PIN diode (Hamamatsu S3590 with $10 \times 10\mathrm{mm}^2$) is used. In addition, a multichannel plate (MCP) in front of a phosphorous screen is viewed by a camera outside of the vacuum chamber (PSRD) up to a rate of 100 Hz. Because of the low intensities the pictures are averaged by the PSRD or in the computer for a reasonable signal to noise ratio. The photon diagnostics for the Aramis beamline was designed and implemented by the photon diagnostic group and is discussed in more detail in [4].

MODELING OF THE ARAMIS UNDULATOR BEAMLINE

The spontaneous undulator radiation is a very important tool to adjust the undulator modules with respect to the correct K respectively gap setting and gives information about the correct alignment of the undulator modules but also of the straightness of the electron trajectory. For systematic studies special python scripts and EPICS tools have been generated to allow a reasonable fast measurements (see Fig. 4). This work was done in collaboration with students from University of Malta which is highly appreciated.



Undulator Alignment (on sf-lc6a-64-03)

Undulator Photon Beam Based Alignment Panel

Select Undulator: ---- E-Beam Energy (Gev): --

Current Parameters

K: -- Gap (mm): -- Height (mm): -- Pitch (mrad): -- Earth Coil (A): --

Scan Parameters

Select K value: 0.0720 go (mm): -- Photon Energy (eV): -- ☐ Third Harmonic

Scan Settings (min, max, inc.)

Gap Scan:	Height Scan:	Pitch Scan:	☐ Earth Coil Scan:	Samples per point:
0.0000	0.000	0.000	0.000	1
0.0000	0.000	0.000	0.000	
0.0005	0.001	0.001	0.001	

Set DCM to (eV): --

☐ Set other undulators to K: 0.072

Use SR Detector: ☐ MCP (PSRD103) ☐ Diode

Waiting to start scan...

x-Axis: ☑ Gap ☐ Height ☐ Pitch ☐ Earth Coil

y-Axis: ☑ MCP Photon Intensity ☐ Keithleys DS Pulse Energy ☐ Diode Intensity

Figure 4: Dedicated panels support a systematic study of the undulators with respect to gap scans, phase matching as well as height and pitch adjustments.

For systematic measurements with spontaneous undulator radiation it is important to reduce the electron beam energy spread by adjusting the compression setup. An example of a gap scan and the corresponding spontaneous radiation distribution distributions are shown in Fig. 5. The 2-dim images allow to control if all undulator modules point in the same direction, Although these rings provide also energy information, at SwissFEL gap scans are used for a K - calibration with higher accuracy.

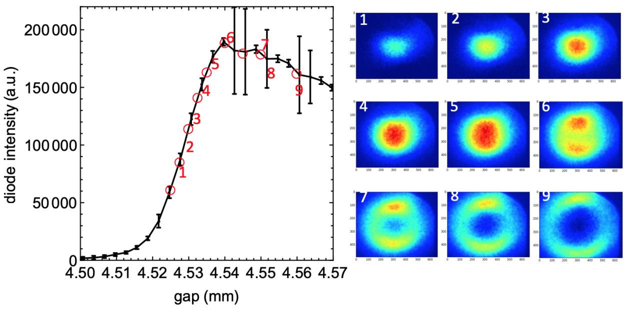


Figure 5: Example of a gap scan at a fixed photon energy of 2.395 keV. On the left side is the diode signal, on the right the corresponding photon distribution measured with the MCP (multi-channel plate).

UNDULATOR SCANS

Height Alignment

Before a fine calibration of the K - value can start the undulator has to be aligned especially in height and pitch. For a planar undulator, the horizontal position as well as the yaw angle does not need further optimisation. The undulator field is also not sensitive to the roll angle which is moreover delicate to adjust because the short bellows which connect the undulator vacuum with the intersections are extremely sensitive in the roll angle. To determine the height of each undulator they are adjusted vertically with the cam-shaft mover by 0.8 mm. The gap scans are done n steps of 20 µm. As the field in the center of the undulator has a local minimum, the resonant wavelength is at the most blue edge if the undulator is well aligned. The height alignment is carried out at the nominal K - value of 1.2 at a gap of 4.5 mm and not at the minimum gap of 3 mm in order to not provoke beam losses. A height measurement is shown in Fig. 6. When the undulator is centered, the good field region is about 50 µm. The time for one gap scan with 40 data points takes about 1 min, for the entire scan about half an hour.

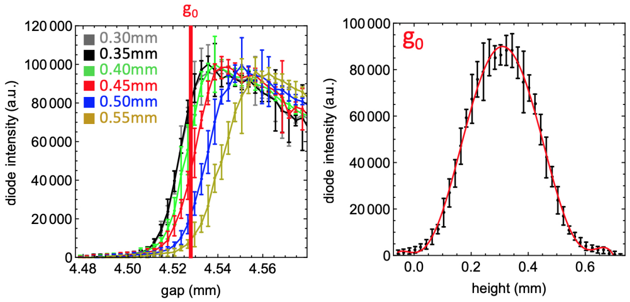


Figure 6: Height alignment of the undulator. Half of the gap scans are plotted on the left side. The field in the vertical center of the undulator gap has a minimum and the resonant wavelength is at its maximum. In a gap scan that means the scan curve is shifted most to the left. On the right, the intensities at a constant gap (g_0) are plotted. The fit delivers the correct height adjustment. This data set was taken at an energy of 2.395 keV.

Pitch Alignment

With a corrected height, the pitch can be adjusted. Again gap scans are done as function of a variation in pitch. The pitch variation shown in Fig. 7 is ±250 µrad. A tilt smears out the blue edge, so the figure of merit is again that the curve is most left in the gap scan plot and has to be the highest slope. Again a fit gives the correct settings. For best results, first the scan range needs to be defined, which should be large enough to get a high contrast. For such scans the precisely remote controlled mover systems pays off.

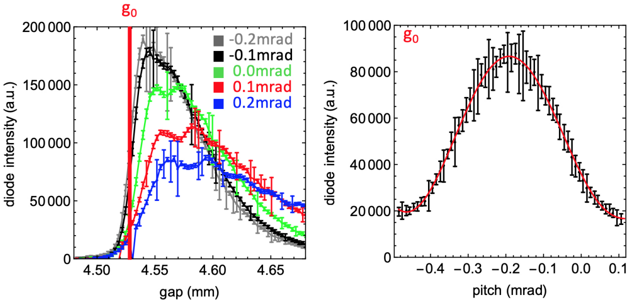


Figure 7: Example of the pitch alignment of the undulator at 2.395 keV. As can be seen is the acceptance in an aligned undulator by 50 µmrad

K Calibration

The K - values have been characterised for the entire working range between $K = 1$ to 1.8 in steps of 0.1, looking at

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the spontaneous radiation intensity downstream a monochromator. With K versus gap measurements as illustrated in Fig. 5, all segments can be calibrated in K to give the same photon energy. For any of these K - values gap scans in the range of ±30 µm are done. With the data from the magnetic measurements the effective blue edge has a width of ±3 µm which corresponds to $\Delta K/K < 8 * 10^{-4}$, see Fig. 8. This calibration is time consuming. Even with prepared experts panels we need two to three shifts for a full characterisation of all 13 undulators.

UNDULATOR ALIGNMENT CAMPAIGNS

So far two major alignment procedures have been carried out with all 13 undulators. During 2018 the electron energy of SwissFEL has been successively increased by commissioning delayed modulators which drive the rf accelerating structures. In March 2018 the maximum electron energy was 2.55 GeV, enough to get into the operating range of the hard x-ray beamline components, so that the first photon based undulator optimisation could be carried out. However, lasing at longer wavelength was achieved already end of 2016 [5, 6].

Campaign March 2018

The first photon based alignment campaign was done in March 2018 at an energy of 2.4 keV. The optimisation was done for a K - value of 1.2 which corresponds to a gap of 4.6 mm. Due to the corrections based on the photodiode measurements of the gain curve, the spread could be reduced by a factor of 2 from ±3 µm to ±1.5 µm or $\Delta K/K < 4 * 10^{-4}$.

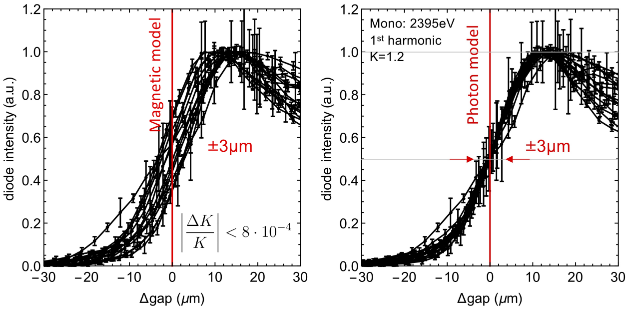


Figure 8: Gap scans with undulators settings based on the magnetic model (top) compared to the results after photon based optimization (bottom). The ±3 µm corresponds to $\Delta K/K < 8 \cdot 10^{-4}$. Based on the measurements, the width of the distribution at the nominal gap could be reduced by a factor of 2.

Campaign January 2019

A second measurement campaign was carried out in January 2019 after the winter shutdown. Now with the full electron energy of 6.15 GeV a photon energy of 13.967 keV was reached. The last 8 undulator modules have been tested for K - values of 1.2, 1.4, 1.6 and 1.8. Note, a K -value of 1.8 corresponds to a gap of only 3 mm. Most of the undulator showed the same spread of ±3 µm as measure one year before, based again on the data from the magnet measurements. But it was found that two undulators, SARUN09 and SARUN14 drifted from previous measurements campaing, see Fig. 9. For higher K - values also SARUN7 shows a drift. The reason for this is unclear. But the undulators have been corrected in the same as in the 2018 campaign.

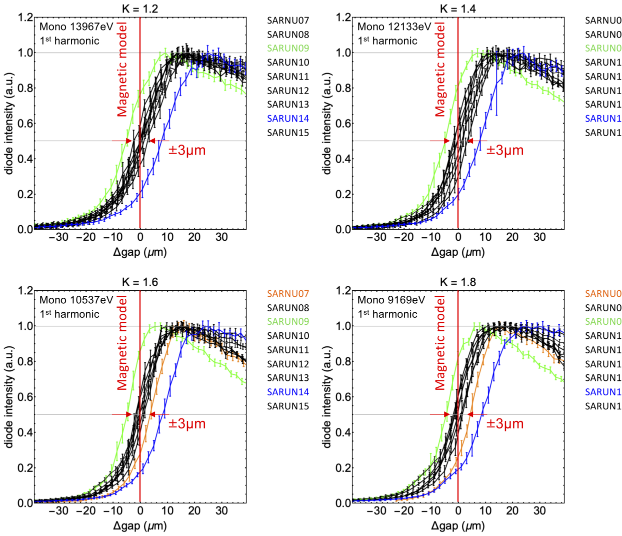
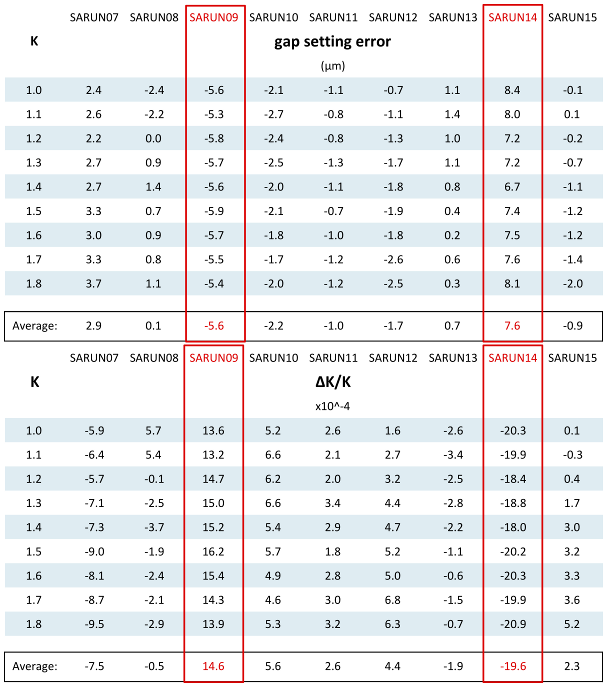


Figure 9: Gap scans for the last 8 out of 13 undulator modules for K - values 1.2, 1.4, 1.6 and 1.8. All measurements are carried out at 6.15 GeV.

The following Fig. 10 shows the resulting corrections:



K	SARUN07	SARUN08	SARUN09	SARUN10	SARUN11	SARUN12	SARUN13	SARUN14	SARUN15
					gap setting error (µm)				
1.0	2.4	-2.4	-5.6	-2.1	-1.1	-0.7	1.1	8.4	-0.1
1.1	2.6	-2.2	-5.3	-2.7	-0.8	-1.1	1.4	8.0	0.1
1.2	2.2	0.0	-5.8	-2.4	-0.8	-1.3	1.0	7.2	-0.2
1.3	2.7	0.9	-5.7	-2.5	-1.3	-1.7	1.1	7.2	-0.7
1.4	2.7	1.4	-5.6	-2.0	-1.1	-1.8	0.8	6.7	-1.1
1.5	3.3	0.7	-5.9	-2.1	-0.7	-1.9	0.4	7.4	-1.2
1.6	3.0	0.9	-5.7	-1.8	-1.0	-1.8	0.2	7.5	-1.2
1.7	3.3	0.8	-5.5	-1.7	-1.2	-2.6	0.6	7.6	-1.4
1.8	3.7	1.1	-5.4	-2.0	-1.2	-2.5	0.3	8.1	-2.0
Average:	2.9	0.1	-5.6	-2.2	-1.0	-1.7	0.7	7.6	-0.9

K	SARUN07	SARUN08	SARUN09	SARUN10	SARUN11	SARUN12	SARUN13	SARUN14	SARUN15
					ΔK/K x10^-4				
1.0	-5.9	5.7	13.6	5.2	2.6	1.6	-2.6	-20.3	0.1
1.1	-6.4	5.4	13.2	6.6	2.1	2.7	-3.4	-19.9	-0.3
1.2	-5.7	-0.1	14.7	6.2	2.0	3.2	-2.5	-18.4	0.4
1.3	-7.1	-2.5	15.0	6.6	3.4	4.4	-2.8	-18.8	1.7
1.4	-7.3	-3.7	15.2	5.4	2.9	4.7	-2.2	-18.0	3.0
1.5	-9.0	-1.9	16.2	5.7	1.8	5.2	-1.1	-20.2	3.2
1.6	-8.1	-2.4	15.4	4.9	2.8	5.0	-0.6	-20.3	3.3
1.7	-8.7	-2.1	14.3	4.6	3.0	6.8	-1.5	-19.9	3.6
1.8	-9.5	-2.9	13.9	5.3	3.2	6.3	-0.7	-20.9	5.2
Average:	-7.5	-0.5	14.6	5.6	2.6	4.4	-1.9	-19.6	2.3

Figure 10: Corrections set according to the blue edge scans of the measurement campaign in January 2019. Most undulators required tiny corrections of 1 to 2 µm, but two needed larger corrections between 5 and 2 µm. The values are also given in units of $\Delta K/K$.

FEL PERFORMANCE

The Aramis undulators work reliable in the full expected gap range down to 3 mm. Systematic wakefield studies especially for the small gaps are still pending. The models based on the magnetic measurement data from the magnetic laboratory including individual gap and phase settings as well as feed-forward corrections allow in general reproducible settings. The drive electronics for the gap drive and mover is located at the undulators support. Problems occurred only with locally to high temperature in the cabinets which could be solved by additional small fans.

Figure 11 i.e. shows a gain curve at the nominal electron energy of 5.8 GeV at 1 Å wavelength. A step by step fit to the slope of the gain curve gave the gain length between SARUN8 and SARUN10 to be excellent 2.2 m, which corresponds to about 2 gain length per undulator module. Pulse energies up to 900 µJ at 3.7 keV and 550 µJ at 12 keV have been reached so far, Figure 12 shows a measurement of the contributions of the individual undulator modules to the FEL signal during setting up the Aramis line for user experiments on July, 15th 2019 at 8 keV with 5.8 GeV electron energy and minimum gap of 3 mm which corresponds to a K - value of 1.8.

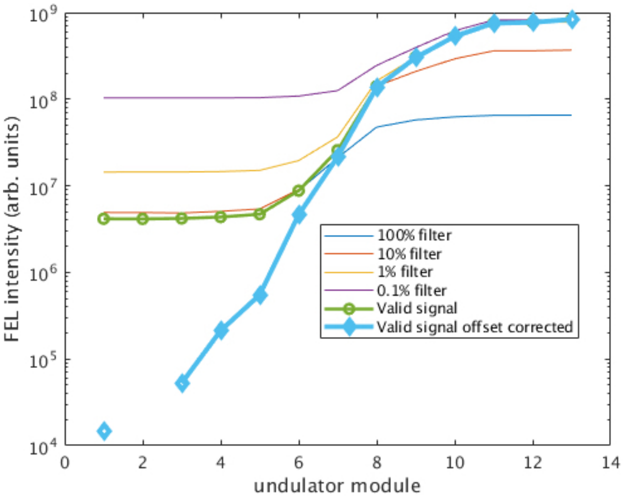


Figure 11: Gain curve measured march 10th 2019 at the nominal electron energy of 5.8 GeV with a charge of 200 pC at 10 Hz. The gain length between SARUN8 and SARUN10 is 2.2 m.

CONCLUSION

The undulators for the SwissFEL Aramis beamline show a good performance. A beam based alignment for the undulators to the electron beam axis can be done with the integrated alignment quadrupoles. The second step is and with photon based diagnostics using the spontaneous synchrotron radiation Height and pitch are straight forward, The calibration of the K - value is more time consuming and suffers from the fact that due to limited optic acceptance not the total flux can be collected. The calibration needs to be repeated regulary, at least once a year. For a daily fine tuning of the FEL signal the PSICO system has been implemented.

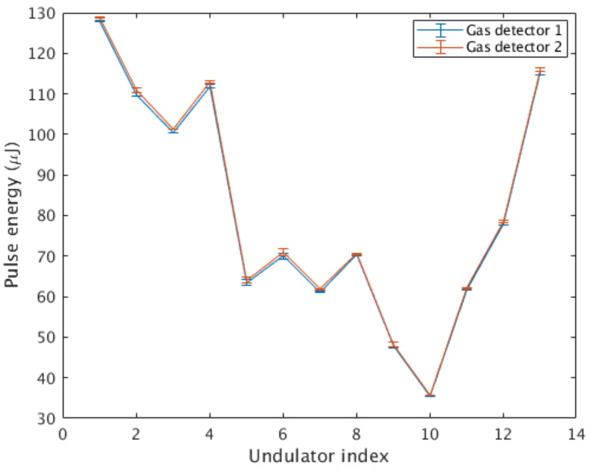


Figure 12: Undulator contribution measured at a pulse energy of 115 µJ only during optimization for user. This plot indicates that the first 4 undulator modules are not contributing.

ACKNOWLEDGEMENTS

Optimisation of the undulators is a common approach of experts from beam dynamics, machine operation, Insertion Devices and photon diagnostics. The authors appreciate also the work of all of those colleagues who are not explicitly in the authors list. And we would like to thank T. Tanaka from RIKEN/SACLA. We followed in many respect his strategies to use the spontaneous light to improve the coherent light.

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