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Operation of the PSI Accelerator Facilities in 2021

Felix Armborst, Antonio Barchetti, Peter Frey, Joachim Grillenberger, Andreas Lüdeke, Didier Voulot, Daniela Kiselev,
Division of Large Research Facilities, PSI

The division of Large Research Facilities is responsible for the operation and development of the four accelerator facilities at PSI: the High-Intensity Proton Facility, the Swiss Light Source, the PROSCAN medical accelerator and the SwissFEL. This article covers operational aspects of the facilities, as well as performance highlights and new developments.

High Intensity Proton Accelerator (HIPA)

In 2021, the overall availability of the High Intensity Proton Accelerator Facility amounts to 92.5% at an average beam current of 1756 μA.

To accommodate the request of the directorate for a longer running period, the start of the user operation was scheduled for 12 April 2021, more than one month earlier than 2020. Despite this tight time plan and the ongoing pandemic, the deadline was met thanks to the commitment and of the involved specialist groups.

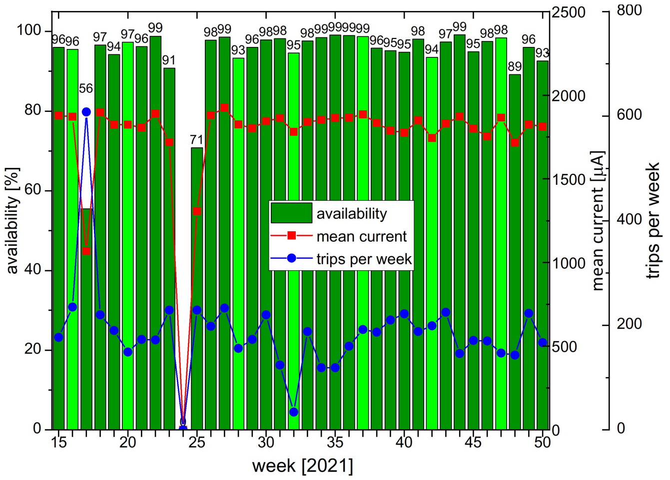

Figure 1: Weekly availability of the High Intensity Proton Accelerator facility in 2021. Already in the first 2 weeks of operation an availability of 96% was achieved. The two major drops in availability were caused by the electrostatic injection channel (70h) and the difficulties in re-commissioning the Ring after the magnet AXA repair (6d).

This is in particular outstanding since an unexpected major issue had occurred during the shutdown.

While re-commissioning Injector 2, an increase of the pressure in the region of the beam stopper BX2 was observed on 2 March. However, the vacuum was still good enough (<10^{-5} mbar) for beam development onto BX2. Unfortunately, a further increase in pressure to 10^{-4} mbar occurred on 12 March. An air leak at the vacuum flange sealing the beam pipe and the channel closure in front of BX2 was localized. The replacement of the sealing could have compromised ceramic water feedthroughs which might have delayed the user operation. Therefore, more powerful vacuum pumps were installed and a Si-based sealing spray was applied to the flange leading to a sufficiently good vacuum pressure of several 10^{-6} mbar. The replacement of the sealing is foreseen for the shutdown 2023 when the construction of a complete spare BX2 is finished.

Figure 2: top view of the region before the beam stopper BX2 (to the right). The yellow area denotes the cooling pipes, which have a high leverage on the ceramic feedthroughs if detached. The colleague is working on the leaking flange.

The user operation started as scheduled on 12 March 2021 and already in the first 2 weeks of operation, an availability of 96% was achieved.

In week 17 of 2021, the electrostatic injection channel EIC had to be conditioned several times at very high dark currents. Presumably, this was due to AQUADAG, which was applied to the inner surface of cavity 5 during the shutdown. Discharges of the electrostatic element EID in Injector 2 were caused by a water leak in week 23. The leak was localized to be in the water cooled coil of the septum magnet AXA. Fortunately, a spare coil was available. However, the repair was critical since the collimator in front of AXA exhibits a high radiation dose of 600 mSv/h. Thanks to the well organized and swift course of action of over 20 specialist, the repair was already finished after 5 days. Nevertheless, the setup of the Ring cyclotron took over 6 days. The setup with standard parameters led to high losses at the extraction of the Ring cyclotron. A measurement of the Ring phase exhibited anomalous behavior (Fig. 3) at which the radial probe RRL was not available for sufficiently systematic troubleshooting. In fact, the Ring trim coils had to be set to unusual values until the full beam was extracted with low losses. The reason for this behavior is yet unknown.

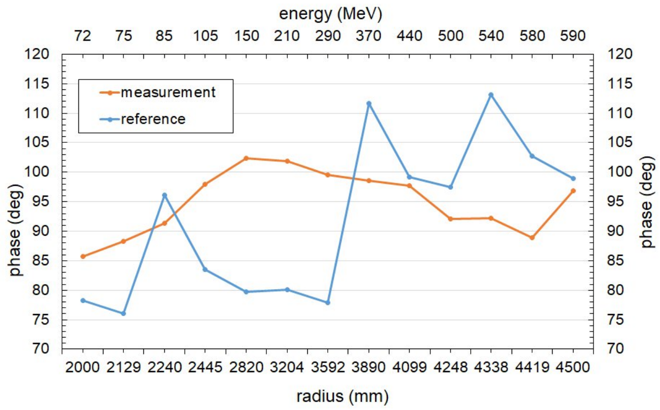

Figure 3: Phase in the Ring cyclotron vs the radius respectively the proton energy. Red denotes the measurement before the incident, blue a curve measured during the setup phase.

It is noteworthy that there was no target failure in 2021. Presumably, this is due to the new ball bearings purchased from the company Koyo, Japan. Those ball bearings use solid-state anti-friction agent and were installed last year.

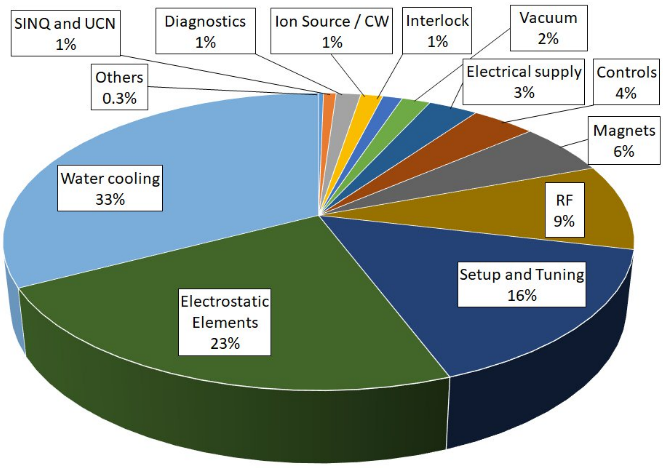

Figure 4: Beam outages per failure category at HIPA.

Figure 4 shows the relative contribution of the different systems to the total downtime. The major contribution to the outages is the water leakage of the AXA-magnet. The setup and tuning problems refer to the difficulties in re-commissioning the Ring cyclotron after the AXA repair.

In week 48 the 90° bending magnets AXC and AXD in the vertical beamline of Injector 2 caused an interlock due to high cooling water temperature. The reason was Copper Oxide that accumulated in the cooling pipes causing low water flow. After flushing the magnet coils several times with fresh water the magnets could be ramped up again. Before the outage, the degassing facility was not in operation, which was most likely the reason for the creation of Copper Oxide. Degassing of the cooling water was re-initiated after the incident.

Table 1: Operational statistics of the High Intensity Proton accelerator Facility for 2021.

Beam-time statistics for HIPA	**2021**
Total scheduled user beam time	**5272**
Beam current integral during the user operation, total	
to meson production targets	9.99 Ah
to SINQ	6.46 Ah
to UCN	0.12 Ah
to isotope production targets	0.013 Ah
Outages (current < 1 mA)	
total time	394.6
total number of outages (t > 5 min)	160
total number of trips (t < 5 min)	6670
Average beam current to meson targets	**1756 µA**
Availability	**92.51%**

The start of user operation for 2022 is scheduled for 12 May. The facility will also run at a maximum beam current of 2.0 mA since the commissioning of the new resonator 2 in Injector 2 is foreseen for 2023, only.

Swiss Light Source

The SLS operational year 2021 proceeded as scheduled, despite the pandemic still raging. In fact the beam availability of 99.3% was the best in the history of the Swiss Light Source. The Mean Time Between Failures was an excellent 7 days. The Mean Time Between Distortions, like beam outages, interruption in top-up or beam orbit distortions, improved to 36 hours.

Only one beam outage during user operation in 2021 was longer than five hours: a short at a 16 kV transformer at PSI West caused a total power outage. This caused a reduction in the available total power and prohibited to switch on the full machine before the transformer could get back into operation. The total beam interruption for the SLS was about 20 hours and 30 minutes, but just 14 hours and 40 minutes were within scheduled user operation.

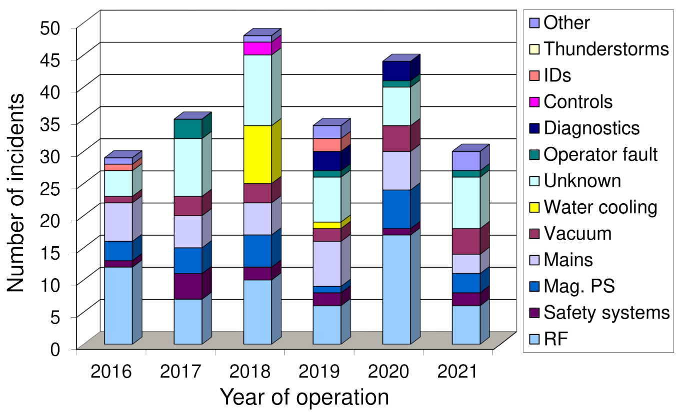

Figure 5: Beam outage count per system for the SLS

Figure 5 shows what subsystems caused beam outages in the past years. For more than a quarter of the outages in 2021 the root cause is unknown. Since the total number of outages is very small (29 in 5008 hours) it is still acceptable. The new orbit feedback system will provide post mortem data on the orbit before the beam loss and therefore improve our capabilities to locate the root cause of beam interruptions.

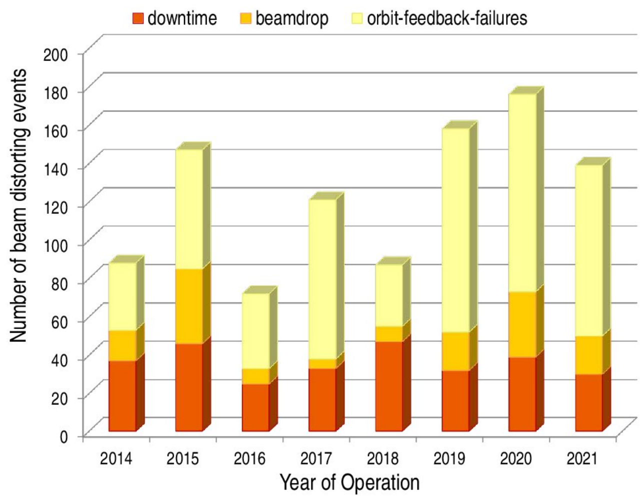

Figure 6: Number of beam distortions at the SLS

Figure 6 shows the count for different beam distortions in the past years. The number of orbit feedback outages has slightly increased in the past three years. Yet there is currently no development to the worse. Many outages are related to the very old BPM electronic hardware. A new system is already in preparation and prototypes have been successfully tested in the SLS. With SLS 2.0 a fully new BPM and FOFB system will go into operation.

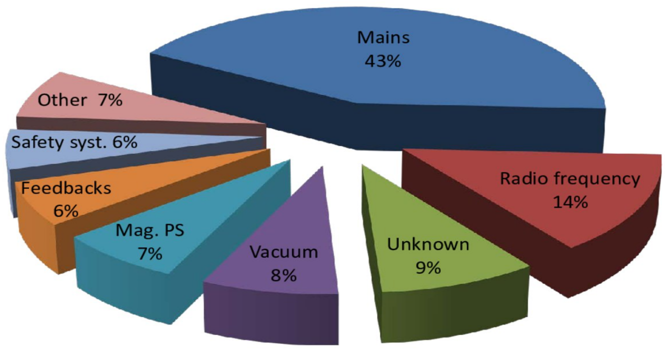

Figure 7: Beam outages per failure category at the SLS

Figure 7 shows the relative contribution of the different systems to the total downtime. About 40% of the downtime in 2021 was caused by a single event: the above mentioned power cut from a short at a 16 kV transformer. No other system showed problems out of the ordinary.

The operational statistics of the SLS is summarized in Table 2.

Table 2: Operational statistics of the Swiss Light Source

Beam Time Statistics for SLS	2021		2020	
Total beam time	6688 h	76.3%	6316 h	71.9%
• user operation	5008 h	57.2%	4652 h	53.0%
- incl. compensation time	144 h	1.6%	144 h	1.6%
• beamline commissioning	728 h	8.3%	760 h	8.7%
• setup + beam development	952 h	10.9%	904 h	10.3%
Shutdown	2072 h	23.7%	2468 h	28.1%
User operation downtimes	29		39	
• unscheduled outage duration	38 h	0.7%	96 h	2.0%
• injector outage (non top-up)	17 h	0.3%	26 h	0.6%
Total beam integral	2472 Ah		2315 Ah	
Availability	99.3%		98.0%	
Availability after Compensation	102.2%		101.1%	
MTBF (mean time between fail.)	167 h		116 h	
MTTR (mean time to recover)	1.3 h		2.5 h	
MTBD (mean time bet. distortions)	36 h		26 h	

Operation of the SLS with Transverse Resonance Island Buckets (TRIBs) [1] has been successfully demonstrated in a machine development shift. Nonlinear beam dynamics feature two independent and stable orbits with magnet optics tuned for a horizontal tune in close proximity to the 3rd order resonance, low horizontal chromaticity, sufficient resonance driving and an appropriate tune shift with amplitude (TSWA). The corresponding TRIBs at the SLS were observed on the pinhole imaging system (see Fig. 8). The visible, vertical separation is due to non-zero coupling. Operation with TRIBs enables straightforward bunch separation for all beamlines and a new class of multi-colour and multi-polarization user experiments, e.g., increasing the helicity flipping rate for X-ray magnetic circular dichroism (XMCD) from the Hz to the MHz regime [2].

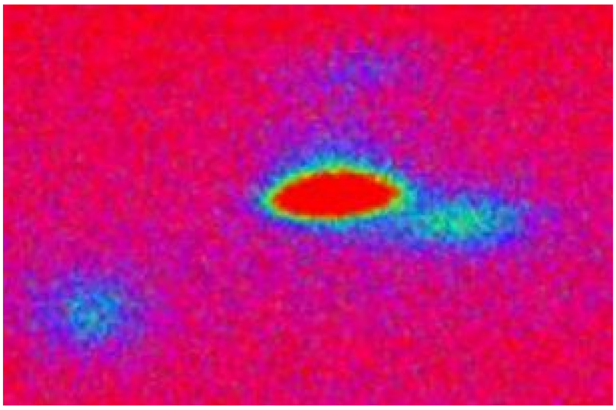

Figure 8: Pinhole image of TRIBs at the SLS.

PROSCAN

In 2021 the cyclotron COMET and its beamlines for the proton therapy facility PROSCAN at PSI have been operating with an uptime of 7440 hours. This includes scheduled patient treatment between Christmas and New Year as every year.

The shown uptime in Fig. 9 reflects the time that cyclotron and beamlines have been in the status “ready for beam delivery”, relative to the scheduled beam time. Downtimes due to interlocks from the patient treatment side are thus not included in these statistics. The availability was 99.0 %, again keeping its high performance since 2013 for another year.

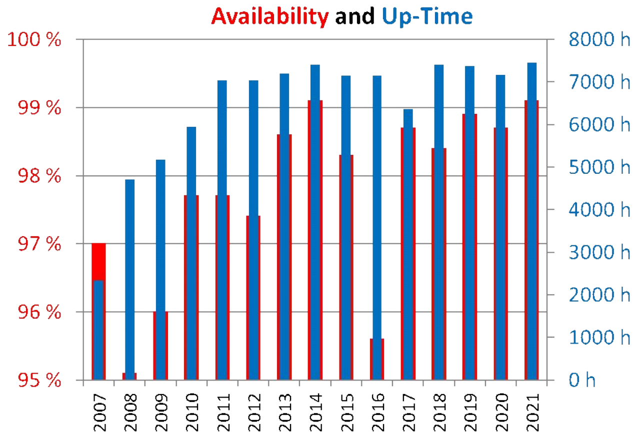

Figure 9: Operating hours per year and availability of PROSCAN.

The causes of the unscheduled downtime of 72 h are shown in Fig. 10. The RF outages were reduced significantly from almost 50 h in 2020 to less than 9 h in 2021. In fact it was just one event, which causes the total downtime for RF related issues in 2021. Fortunately, it did not disturb the patient treatment as it happened on the weekend.

In 2020 the operation still suffered from problems in beam alignment in the Gantry 3 and/or to its coupling point causing interlocks and delaying the patient treatment. It was difficult and not always possible to understand the cause of these interlocks since the Gantry 3 control system was not able to provide the relevant time-stamped data. This issue could be finally solved with the supplier of Gantry 3, Varian. Therefore, no worth mentioning downtime due to beamline related issues was acquired in 2021 while it summed up to an unscheduled downtime of 13 h in 2020. In addition, a new procedure for beam alignment is under development and first tests were already performed. If fully tested and successful, it will be implemented in the operation strategy.

The downtime for controls increased by a factor of three, however, this is caused by a few events, e.g. a failure of the patient safety system due to an erroneous reading of a current monitor in Gantry 2, which took 7 h of trouble shooting and repair. The time for non-scheduled maintenance of the ion source is similar to 2020. Five unplanned services were needed, however, they were scheduled in such a way that the influence on the patient treatment was minimal.

In 2021 there were two power outages (4.3.21 and 8.12.21). As usual in such cases PROSCAN has priority, if patients are scheduled for treatment. In the first event the power line was switched within 10 minutes to another source and after 4.5 h of tuning the cyclotron was ready for operation. In the second event power was restored after half an hour and after several reboots of the control system and additional beam tuning patient treatment could continue after 3 h.

Altogether there were 33 weeks without downtime due to failures.

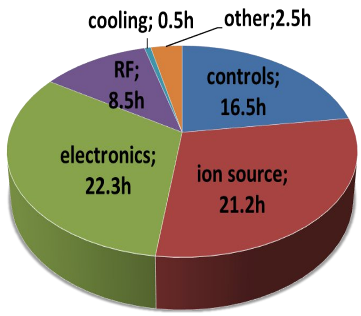

Figure 10: The unscheduled downtime for 2021 by causes.

Over the last 2 years the phase measurement built-in by the supplier of the cyclotron degraded due to a varying background signal of unknown source. It is based on a pick-up tuned to the 2nd harmonic of the RF and analogue signal processing, which was replaced by a fast digital lock-in system on the 3rd harmonics. This new measurement set-up turned out to be sensitive to currents as low as 10 nA, which corresponds to the proton currents during stand-by of COMET to avoid activation while waiting for the next patient treatment. The phase is stabilized using a feedback system regulating the cyclotron magnet current and operated via script in the control room. Since spring 2021 this feature is in routine operation reducing the time needed for tuning after a longer stand-by.

For the so called FLASH experiments an approximately 1000 times higher dose rate is applied in a short time. At PROSCAN 250 MeV beam pulses of 800 nA during few milliseconds are transported to Gantry 1 and the effect on living organism is studied. To measure such high currents a non-interceptive beam current monitor is advantageous to avoid charge accumulation and subsequent non-linear behaviour. The current monitor developed at PSI [3] is based on a resonant cavity tuned to the 2nd harmonic of the proton beam pulse rate. First tests under beam conditions for FLASH seem to be promising.

To make FLASH experiments feasible at lower energy the transmission needs to be increased significantly. Beam simulations revealed that a new collimation system, asymmetric in both beam size and divergence, replacing the one after the degrader could increase the transmission by a factor of 6 at 70 MeV, i.e. from 0.13 % actually to 0.72 % [4]. Together with a new beam optics design it allows a better matching to the beamline acceptance and the requirements of Gantry 2.

SwissFEL

Several important milestones were achieved in 2021. The Athos undulator line was completed: the 16th and last Athos undulator was installed in April. Maloja started regular operation with a first user run in February and, in total, five runs were successfully completed by the end of 2021. In June, the first photon beams reached the Furka end-station. The commissioning of the beamline is now completed and the end station commissioning is on-going. The installation of Cristallina was completed in the winter shutdown and the first beam time is scheduled in March. In total five end-stations will take beam in 2022 at SwissFEL.

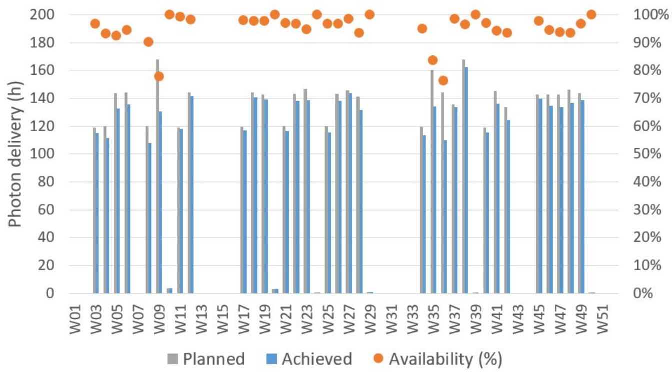

Figure 11: SwissFEL Aramis operation statistics during photon delivery weeks in 2021.

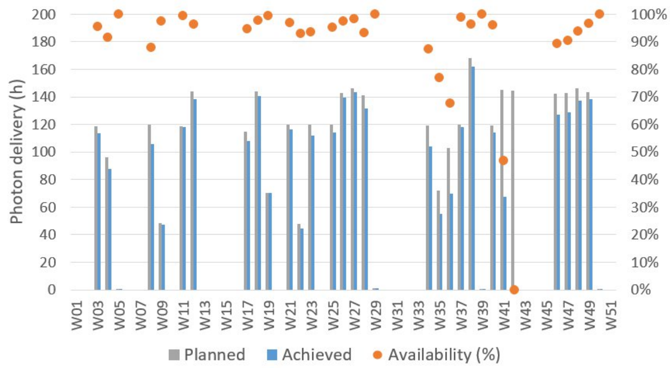

Figure 12: SwissFEL Athos operation statistics during photon delivery weeks in 2021.

With the increasing number of beamlines in operation, parallel operation of Aramis and Athos is now crucial. Although parallel operation was already demonstrated in 2020, it remained challenging especially due to beam losses in Athos, which often prevented operating at 100 Hz. Thanks to major progress in 2021, parallel operation is now established and both FEL lines can operate routinely at 100 Hz without problems. The acceleration of two bunches in the same RF pulse is a specificity of SwissFEL and was one of the major challenges of the SwissFEL design.

After the decrease in beam delivery due to the pandemic in 2020, the number of hours of beam operation is increasing again. Aramis reached 4295 h of beam time in 2021. This is more than 2020 (3313) and 2019 (3885). In total, including the user set-up time, beam operation represents for the first time more than 50% of the year on Aramis. Athos reached a total of 3380 h of beam operation in 2021. Despite a number of incidents, the beam availability remains very high for Aramis at 94%. Athos beam availability is somewhat lower at 87.5% but this is mostly due to one single incident: a vacuum leak in the SATUN19 undulator in October, which cost about two weeks of operation for Athos. Outside a few single incidents, the availability of the beam is very high, often above 95%. This is testimony to the reliability of the systems and the excellent support from the technical groups. Figure 11 and 12 summarize the beam availability during weeks dedicated to photon delivery (user operation and beamline development) for Aramis and Athos.

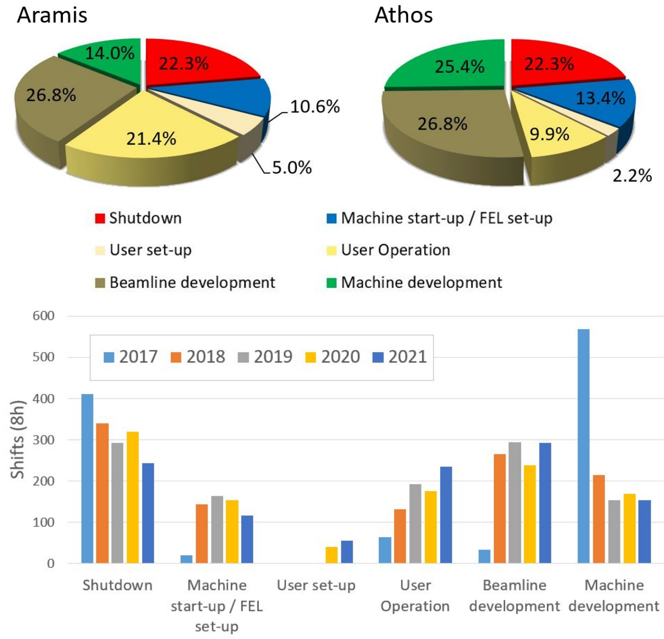

Figure 13: Shift distribution in Aramis and Athos in 2021 and evolution of the shift distribution for Aramis in the period 2017–2021.

The rest of the year was shared between shutdowns (22.3%), machine development and set-up. The share of machine development is decreasing for Aramis (14%) but remains significant for Athos (25.4%) where some systems still need to be commissioned and special operation modes need to be developed and tested. The shift distribution is shown in Fig. 13.

The fraction of shutdowns decreased again in 2021 (22.3%). In particular, the number of service days was reduced to three to minimise the number of machine start-ups. In spite of this, major installation work took place in 2021. The Athos undulator line was completed, the X-band deflector installation has started and should be achieved in the summer of 2022, the Furka and Cristallina beamlines were completed and the HERO and EEHG installation made important progress.

2021 saw also large progress in terms of machine operation. Not only parallel operation was established as standard operation with 100 Hz on both lines but also the reliability and reproducibility of the machine has vastly improved. Start-ups after machine shutdowns got faster and more reliable: lasing on both lines is often achieved within 2 days of the start-up (6 days are normally scheduled for the start-up). Photon energy changes, both from electron beam energy scaling or undulator gap scaling, are now automatized and can even be done directly by the end-stations with good reliability on both FEL lines. In 2021 and especially at the end of the year a number of new intensity records were set. For example, 1.4 mJ at 7.5 keV or 775 µJ at 12 keV could be achieved in Aramis, 3 mJ at 0.54 keV could be achieved in Athos. Lasing up to 15 keV could be demonstrated on Aramis. These performances are largely exceeding the CDR design goals and commissioning objectives of the machine. Pulse energies in excess of 1 mJ are now routinely produced in both undulator lines.

These good performances were made possible thanks to progress in the understanding of the machine and improvement of the operation procedures. In particular, notable progress was made in the beam-based alignment of the undulator lines and the optimisation of the electron orbit to maximise lasing. This was instrumental in achieving record lasing levels while keeping beam losses acceptable in the undulators. Another large fraction of the machine development was dedicated to the further commissioning of Athos and especially the development of new modes. This led to the realisation of an experiment in which, thanks to the CHIC magnetic chicanes, two FEL pulses of different wavelengths were generated simultaneously and sent to a sample with a controlled time offset of a few femtoseconds. This success demonstrates the great potential of the CHIC method, which has so far only been implemented in the SwissFEL Athos line.

The main goal of 2022 will certainly be to maintain the high performance level achieved last year over long periods in user operation. The 2022 planning will see an increase of user operation and beamline development shifts on both Aramis and Athos. Delivering beam reliably to five beamlines will certainly be a challenge.

References

[1] F. Armborst, *Transverse Resonance Island Buckets at BESSY II*, Dissertation, Humboldt-Universitat zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät, 2022, https://dx.doi.org/10.18452/23851

[2] K. Holldack et al, *Flipping the helicity of X-rays from an undulator at unprecedented speed*, Comm.Phys. 3, 61 (2020), https://doi.org/10.1038/s42005-020-0331-5

[3] S. Srinivasan, P.-A. Duperrex, J.M. Schippers, *Beamline characterization of a dielectric-filled reentrant cavity resonator as beam current monitor for a medical cyclotron facility*, Physica Medica 78 , 101 (2020), https://doi.org/10.1016/j.ejmp.2020.09.006

[4] V. Maradia, D. Meer, D.C. Weber, Antony J. Lomax, J.M. Schippers, S. Psoroulas, *A new emittance selection system to maximize beam transmission for low-energy beams in cyclotron-based proton therapy facilities with gantry*, Med Phys. 48, 7613 (2021), https://doi.org/10.1002/mp.15278