Operation of the PSI Accelerator Facilities in 2022

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 Accelerator 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)

Clouded by the energy crisis, the High Intensity Proton Accelerator Facility (HIPA) excelled yet with an unprecedented availability of 94.4% with an average beam current of 1756 µA in 2022. At this juncture, it is worth mentioning that in eleven out 34 weeks of operation an availability of over 98% was achieved.

User operation started as scheduled on 2 May 2022. During the first week of commissioning, the accelerator already delivered stable beam onto the beam dump. Due to a defective Quick Shutter Valve in front of the neutron spallation target SINQ the SINQ-tests had to be resumed which delayed regular user operation by 4.7 h. In addition, the amplifier chain of resonator 4 in Injector 2 had to be repaired leading to a further 8.4 h of downtime. In total, the availability of the first week of operation amounts to 80%.

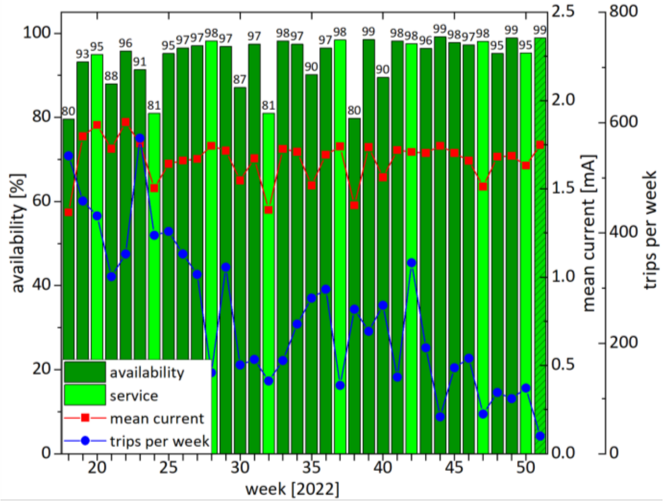

Figure 1: Weekly availability of the High Intensity Proton Accelerator Facility in 2022. Due to the energy limitation, the facility was shut down on 19 December, 5 days earlier than scheduled (dashed lines represent last week of operation with only 3 days).

During the shutdown 2022, a burnt conduction layer inside the acrylic glass tube of the Cockcroft-Walton pre-accelerator was removed by polishing. This layer was already detected in 2021, and was at that time bypassed with a hot-wire to continue user operation. The replacement of the tube has been taken into consideration but proves to be difficult since no supplier could be found up to now.

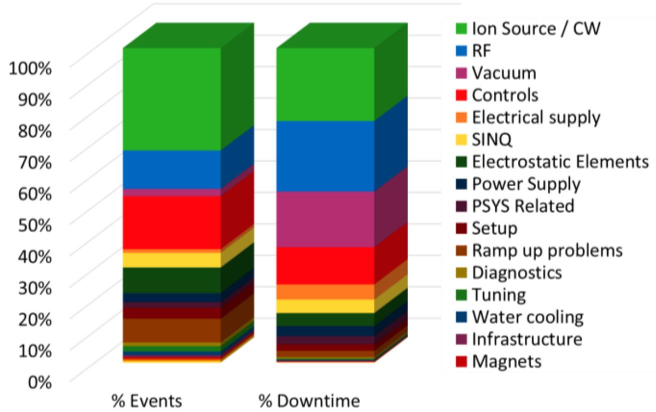

Figure 2: Beam outages per failure category at HIPA. The vast majority of failures on the ion source were due to interlocks induced by high voltage instabilities of the electron trap.

Similar circumstances prevented the repair of the beam stopper BX2 of Injector 2. The necessary parts for the spare BX2 did not arrive at PSI in time, for these reasons the foreseen replacement of the leaking gasket has been postponed to the shutdown of 2024.

Table 1: Operational statistics of the High Intensity Proton accelerator Facility for 2022.

Beam-time statistics for HIPA	**2022**
Total scheduled user beam time	**4784**
Beam current integral during the user operation, total	
to meson production targets	8.0 Ah
to SINQ	5.5 Ah
to UCN	0.15 Ah
to isotope production targets	0.01 Ah
Outages (current < 1 mA)	
total time	268
total number of outages ($t > 5$ min)	193
total number of trips ($t < 5$ min)	8489
Average beam current to meson targets	**1672 µA**
Availability	**94.4%**

Regarding the outage statistics (Fig. 2), interlocks on the ECR-ion source contribute the most to the downtime of the facility in 2022. The vast majority of these interlocks was caused by discharges of the electron trap located inside the acceleration tube of the Cockcroft-Walton pre-accelerator. In fact, these discharges were detected by the radiation protection system that measured higher x-ray doses (up to 70 µSv/h) outside the Faraday cage. In order to avoid frequent interlocks the electron trap was finally switched off since it is not required for beam operation. Consequently, the access to the Cockcroft-Walton was prohibited during operation to avoid irradiation of personnel with Bremsstrahlung caused by residual electrons accelerated by the high voltage.

Presumably, the electron trap exhibits extensive depositions of sputtered debris, especially on the high-voltage insulators, after more than 30 years of operation. A new electron trap was manufactured at PSI and will be installed during the shutdown 2023. Noticeably, failures of the control system contribute at a level of 20% to the number of events and cause 12% of the total downtime. Many of these systems are outdated and need upgrades in the near future.

In the Ring cyclotron, two important milestones have been reached: First, the Indium based sealing between sector 2 and sector magnet 5 has successfully been installed and proves to be airtight. Thus, a yearly replacement of the Viton O-rings is not required anymore, with a corresponding reduction in personnel dose. Second, the long radial probe RRL in the same sector was successfully commissioned and can now be used to measure the beam profile along the radius of the cyclotron (Fig. 3).

In week 21 the micro wave amplifier for the ECR-ion source had to be repaired (8 h) on-site since no spares are available anymore. New solid-state amplifiers are currently being tested at PSI and are going to be installed in 2024.

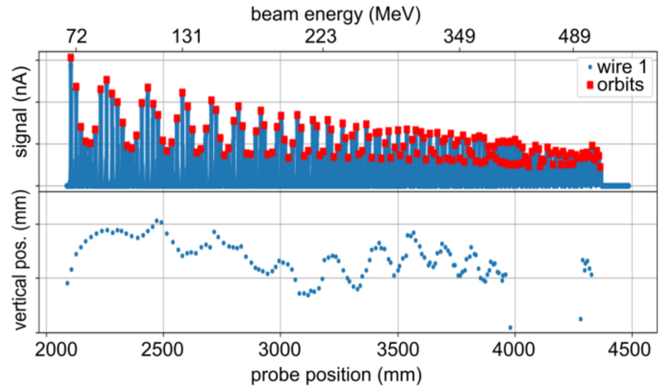

Figure 3: Measurement of the radial beam profile (upper plot) in sector two with the new probe RRL. The probe is equipped with 3 wires. One wire is positioned vertically; the other 2 are rotated by 90° against each other. With this setup, the vertical position (lower plot) of the beam can be measured simultaneously.

The failure of a control unit of the amplifier of Resonator 4 caused 8 h of beam interruption in week 24. Since the unit is more than 30 years old and no documentation is available, it was decided to continue operation without Resonator 4. Therefore, the beam current had to be reduced to 1.8 mA for the rest of the year. Furthermore, a transition module for the beam current monitor MXC2 had to be replaced (2 h).

After 5 weeks of smooth operation with an availability of up to 97%, the magnetron of the microwave amplifier (ECR-source) had to be replaced (16.5 h). In service week 32, a relay of the high-voltage switch for the beam splitter EXT had to be replaced, causing 3 h of beam interruption.

During the following 4 weeks of operation, an increase of apparent losses near cavity 5 (flattop Ring cyclotron) and a higher RF-power consumption was observed. This indicates multipacting effects inside the old aluminium cavity, which frequently occurred in the past 10 years. Therefore, the inner surface of the flattop was treated with Aquadag during the service period of week 37.

During the following week, the ceramic of an RF pickup within this cavity cracked, leading to an air leak. The replacement and re-commissioning caused 28 h of beam interruption.

To save energy, it was decided to skip the scheduled beam development in week 47. Unfortunately, the flattop had to be re-treated with Aquadag during this week, which required successive conditioning and thus consumption of energy. This was partially compensated by the thorough efforts of all specialist groups including experimentalists who rigorously switched-off all electricity loads not needed during the service.

Both meson production targets (TgE and TgM) worked smoothly during the whole year. Like in 2021, the new TgE ball bearings, purchased from the company Koyo, proved to be reliable and ensured stable operation throughout the running period. The established "slanted" technology, employed in TgE, provides a 40 to 50% increase of the surface muon rates compared to the traditional "slab" technology. Moreover, for the first time the slanted TgE was furnished with tiny grooves (in the middle) and shims (on the left and right sides) that, if hit by the beam, introduce a small transmission modulation whose frequency differs for the three cases. This makes it possible to recognize whether the beam is correctly centred or if it wandered to one side, with the risk of bypassing the target.

The start of user operation for 2023 is scheduled for 25 May. This date is comparatively late and was chosen to save energy.

The new tuner systems for the new resonators in Injector 2 were successfully tested and will be installed during the shutdown 2023. Therefore, the facility can again be operated at a beam current of 2.0 mA with the new Resonator 2 in operation. In addition, Resonator 4 is going to be equipped with a new solid-state amplifier. If the commissioning of both resonators is successful, higher beam currents of up to 2.2 mA will be feasible and are foreseen during beam development shifts in 2023.

Swiss Light Source

The SLS operational year 2022 proceeded as scheduled, despite the pandemic still raging until April and despite the energy and other crises caused by Russia's invasion of Ukraine. The beam availability of 97.3%, whilst being the worst since 2013 in the history of the Swiss Light Source, remains comparable to other light sources. With four days the Mean Time Between Failures was good. The Mean Time Between Distortions, like beam outages, interruption in top-up or beam orbit distortions, remained with 27 hours at more than a day.

Only two beam outages during user operation in 2022 lasted longer than five hours: The beam path was blocked after a foil of the undulator 04SA-ID ripped, causing the longest outage of 56 h. The ID was removed and replaced with vacuum chamber. The shorter 11 h outage was caused by a power supply failure of the ring quadrupole magnet ARIMA-QMF-02. The repair of the connectors and transformer could not be performed alone by the on-call expert during the night and was successfully finished the next day. Another significant incident of 2022 was a mishap involving the superconducting third harmonic cavity (S3HC). During a machine development shift with experimental orbit bumps, multiple errors coincided, thereby enabling too large orbit excursions in the vicinity of the S3HC. The vacuum controller failed to interlock the beam and up to 1E-5 mbar was observed at the absorbers before and after the S3HC. Since this incident the S3HC shows a permanent asymmetry in voltage between the two cavities and thus requires manual tuning by the operators until reaching equilibrium some 10 minutes after accumulation of nominal beam current.

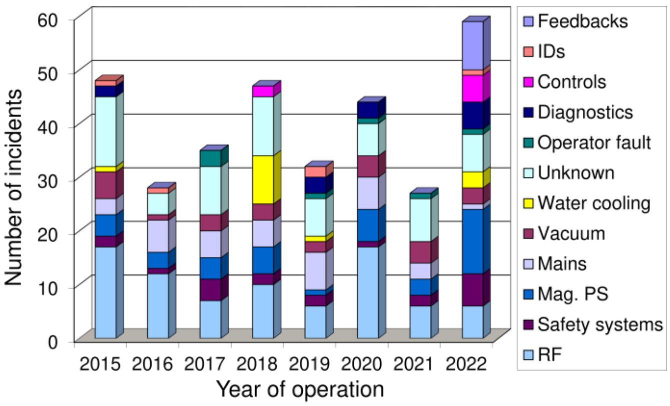

Figure 5: Beam outage count per system for the SLS

Figure 5 shows what subsystems caused beam outages in the past years. In total almost 60 outages during the 4960 hours of user operation in 2022 were recorded. Many of these outages are directly (in-situ testing of new hard- and software) or indirectly (reduced maintenance) related to the upcoming upgrade project SLS 2.0, for which the existing SLS will make way end of September 2023.

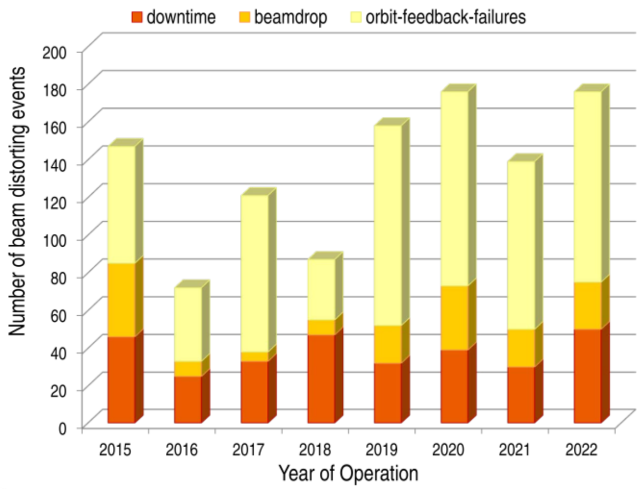

Figure 6: Number of beam distortions at the SLS

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 four years. Despite 2022 being the last full year of operation for the SLS no deteriorating trend can be seen. Many outages are related to the very old BPM electronic hardware. The new system is already in preparation and prototypes have been successfully tested in the SLS. With SLS 2.0 a completely new BPM and FOFB system will go into operation.

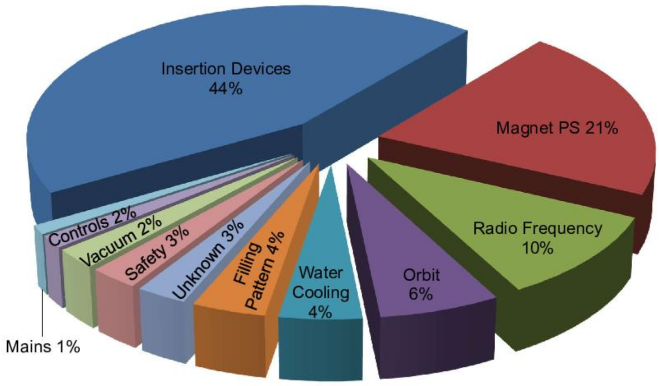

Figure 7: Beam outages per failure category at the SLS

Figure 7 shows the relative contribution of the different systems to the total downtime. Almost 50% of the downtime in 2022 was caused by a single event: the aforementioned blocking of the beam path after a foil of the undulator 04SA-ID ripped. 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	2022		2021	
Total beam time	6512 h	74.3%	6688 h	76.3%
• user operation	4960 h	56.6%	5008 h	57.2%
- incl. compensation time	96 h	1.1%	144 h	1.6%
• beamline commissioning	744 h	8.5%	728 h	8.3%
• setup + beam development	680 h	7.6%	952 h	10.9%
Shutdown	2248 h	25.7%	2072 h	23.7%
User operation downtimes	50		29	
• unscheduled outage duration	128 h	2.6%	38 h	0.7%
• injector outage (non top-up)	13 h	0.2%	17 h	0.3%
Total beam integral	2373 Ah		2472 Ah	
Availability	97.4%		99.3%	
Availability after Compensation	99.3%		102.2%	
MTBF (mean time between fail.)	97.3 h		167 h	
MTTR (mean time to recover)	2.6 h		1.3 h	
MTBD (mean t. betw. distortions)	27.3 h		36 h	

PROSCAN

In 2022 the cyclotron COMET and its beamlines for the proton therapy facility PROSCAN at PSI have been operating with an uptime of 7474 hours. This includes scheduled patient treatment between Christmas and New Year as every year.

The uptime in Fig. 8 reflects the time that cyclotron and beamlines were in the state "ready for beam delivery", in the period scheduled for beam. It is the highest uptime since the start of the COMET for proton therapy in 2007. Downtimes due to interlocks from the patient treatment side are not included in these statistics. With 98.0% the availability was the lowest since 2017, but it still represents a very solid performance for such a complex facility. During 23 weeks, there was no failure at all. This good performance is only possible due to maintenance during weekends and evenings as well as due to the fast action of on-call expert teams in case of a failure.

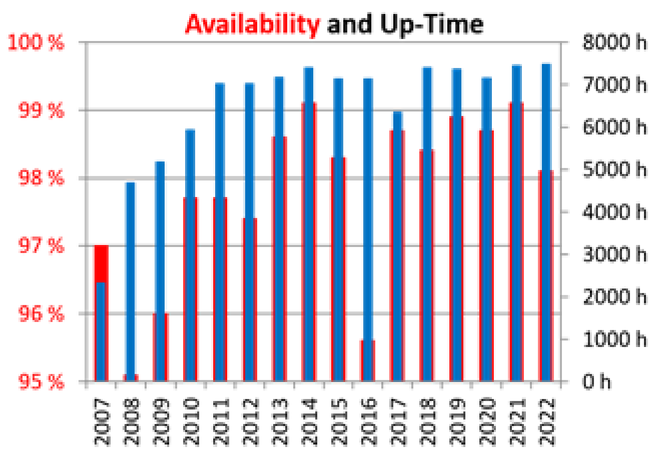

Figure 8: Operating hours per year and availability of PROSCAN.

The causes of the unscheduled downtime of 162 h are shown in Fig. 9. The outages due to electronics reduced significantly from 22 h in 2021 to 8 h in 2022. Failures due to the control system, however, increased by another factor three in 2022. This trend had already been observed in 2021. Controls issues contributed a third to the downtime, the other third was caused by problems related to the ion source. Altogether, 14 unplanned ion source services were necessary, however, only three in the second half of the year. In the first quarter of the year, the ion source suffered from many falsely triggered rapid shutdowns caused by a controls problem. This effect is known to shorten the lifetime of the ion source and caused many services, four of them disturbing patient treatment. End of April a new central patient safety system was installed and the problem of falsely triggered rapid ion source shutdowns disappeared. In the second quarter the hydrogen gas supply for the ion source was replaced. For five weeks the ion source failed several times after only short operation, sometimes parts were even damaged due to bad vacuum conditions and dirt. Finally, the reason was found to be related to gas pipes requiring a special cleaning procedure, which was not known before. The gas supply system was dismounted, the old one installed and later replaced by a new one consisting of ultraclean components.

A power outage of 8 minutes occurred in the afternoon of January 4, affecting all of PSI. As usual in such cases PROSCAN has priority if patients are scheduled for treatment. Fortunately nothing was damaged and beam could be restored after 3 h.

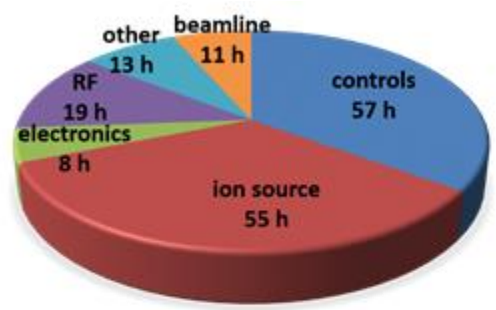

Figure 9: The unscheduled downtime for 2022 by causes.

In Table 3 the key data for the performance of COMET are summarized. The listed beam current integral corresponds to the beam on degrader and first beam stopper after the cyclotron, which is a good representation of the total charge extracted from COMET.

Table 3: Operational statistics of COMET

Beam time statistics for COMET	2022
Scheduled beam time	7636 h
Beam current integral	209.3 µAh
Up-Time	7474 h
Outages	162 h
Availability	98.0 %

Since the COMET cyclotron delivers a constant energy of 250 MeV, the energy has to be reduced and varied fast according to the requirements of the proton therapy treatment, e.g. for OPTIS, the treatment of eye melanomas, 70 MeV is needed. At present, energy modulation is done via a degrader, which consists of several movable graphite wedges. This allows for a fast variation of the effective graphite thickness in the beam, resulting in rapid energy modulations between 70 and 230 MeV. However, due to multiple scattering part of the beam is lost at the degrader or later in the beamline due to the energy spread and increased angular divergence. For 70 MeV the transmission is around 0.2%, depending on the acceptance of the beamline. In [1] simulations predicted a significant increase of the transmission for a degrader made from boron carbide (B_4C), by 37% for 84 MeV. Such a degrader was recently completed (Fig. 10).

Figure 10: Degrader with B_4C wedges in closed position, i.e. maximum thickness. The beam passes horizontally.

In October, the degrader was successfully installed and the driving mechanics was tested as well. First tests with beam indicate an increase of the transmission of at least 30% for 70 MeV protons. The tests were performed during two weekends to avoid disturbance of patient treatments. For this, the degrader had to be installed and dismantled twice, nota bene after the graphite degrader was removed. The clinical implementation is expected in Q3/2023.

Several tests in the beamline to Gantry 2 were performed for the new non-destructive low-beam-current monitor (BCM), which was developed as part of a collaboration between Bergoz Instrumentation, Paul Scherrer Institute and Instrumentation Technologies [2-3]. Originally, the BCM was developed and successfully tested for very low currents (down to 0.15 nA). However, since it has a fast response and does not show saturation, measurements at higher currents and short pulse durations similar to beam conditions for FLASH experiments could be demonstrated. Indeed, currents up to 800 nA supplied in short pulses between 1 and 20 ms, or 50 ms, were successfully tested already. The tests will continue to measure the linearity of the device more precisely.

SwissFEL

Several important milestones were achieved in 2022. The baseline machine was completed, with the installation and commissioning of the last components of the Athos line. The Athos tuning linac, consisting of one C-band RF station providing ±240 MeV energy adjustment to the 3.15 GeV extraction energy of the Athos beam, started operation successfully in 2022. The station could not reach its full power in 2022 due to a faulty waveguide section. The waveguide part was replaced in the winter shutdown so that the station is expected to reach its design energy in 2023. The transverse deflecting cavity, an X-band structure developed in collaboration with DESY and CERN (Polarix design), was commissioned in 2022. The station provides high-resolution longitudinal diagnostics of the post-undulator bunch. A preliminary temporal resolution of 1 fs was already demonstrated. The HERO/EEHG project has also made large progress in 2022 with the completion of the HERO installation in spring and the demonstration of slicing and ESASE to produce trains of attosecond pulses later on. The installation of the second phase of the project, the EEHG modulator and chicane is underway, and the first EEHG pulses in Athos are expected in spring 2023.

The number of endstations keeps increasing: five endstations received beam in 2022. In March, Cristallina saw its first X-ray beam and in the same month Maloja successfully completed its first user experiment (peer-reviewed proposal). There were a total of 18 user runs in Aramis and six in Athos in 2022. Major installation work took place at the Furka endstation during the summer with the installation of the RIXS spectrometer. Furka is expected to run its first pilot experiment in March 2023.

The beam time reached new records in 2022. Aramis achieved a total of 4484 h of beam operation in 2022. This is to be compared with 4295 h in 2021 and 3313 h in 2020. (This is actually even better, as the beam time for 2022 does not include any user set-up time, contrary to what was done in previous years.) Overall, the share of beam operation represents 51.2% of the year in Aramis.

Athos reached a total of 3569 h of beam operation in 2022 (compared to 3380 h in 2021) or about 40.7% of the year.

The beam availability also improved in 2022, with an overall beam time availability of 94.5% for Aramis (94.0% in 2021). Athos availability improved even more significantly, reaching 92.2% in 2022 (87.5% in 2021). As in previous years a few major incidents account for a large share of the downtime. An offset mirror failure in the Athos optics hutch caused two weeks of downtime in September. This could be partially mitigated by swapping the time with machine development time, as the machine and photon beam (up to the front-end) remained available. On a few more occasions this year the machine narrowly escaped major down times. A failure of the SwissFEL master oscillator following the yearly electrical switch test (August), the loss of the superperiod lock for some RF stations (September), S-band klystron failures in the gun (September) and SINSB04 stations (October) could all have led to major downtimes. Thanks to the fast and competent intervention of the corresponding support groups, the machine could be restarted swiftly in all cases and the downtime was limited to a few hours.

Outside these incidents, the beam availability remained very good, often well above 95%. This was the case for example in the last few weeks before Christmas for the Athos line. Figures 11 and 12 summarize the beam availability during weeks dedicated to photon delivery (user operation and beamline development) for Aramis and Athos, respectively.

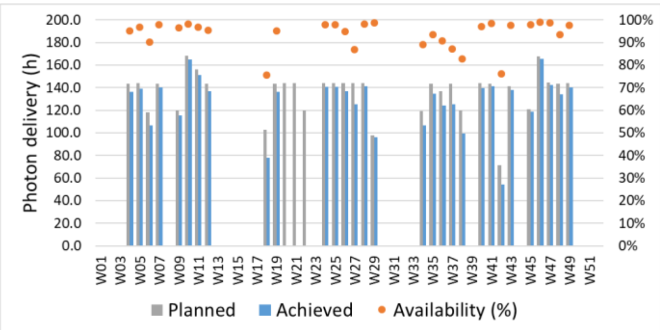

Figure 11: SwissFEL Aramis operation statistics during photon delivery weeks in 2022.

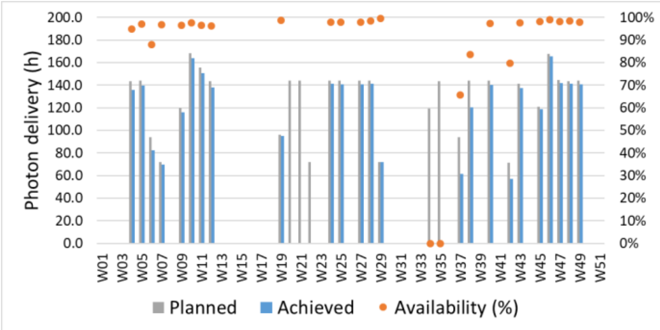

Figure 12: SwissFEL Athos operation statistics during photon delivery weeks in 2022.

The remaining time, not covered by photon beam delivery, breaks down into shutdowns (21.6%), machine development (13.2% for Aramis, 22.5% for Athos) and set-up (14.2%). The share of machine development is decreasing slightly in both lines but remains significant for Athos. In Athos some systems still need to be commissioned and special operation modes are in active development. Furthermore there is only one endstation in full operation, leaving more beam time available for beam development studies. The shift distribution is shown in Figures 13 and 14.

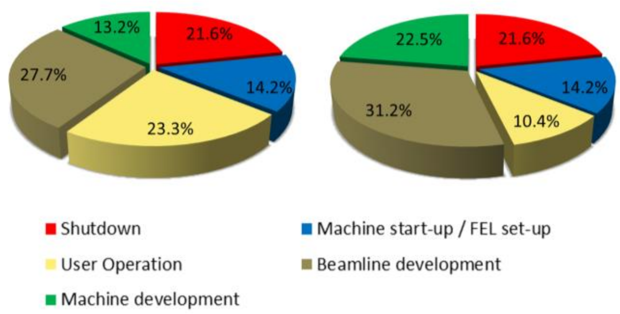

Figure 13: Shift distribution in Aramis (right) and Athos (left) in 2022.

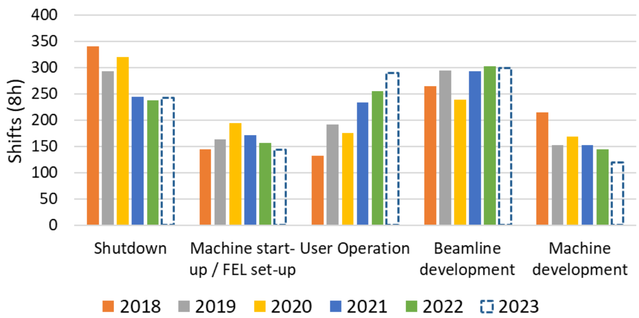

Figure 14: Evolution of the shift distribution for Aramis in the period 2018–2023.

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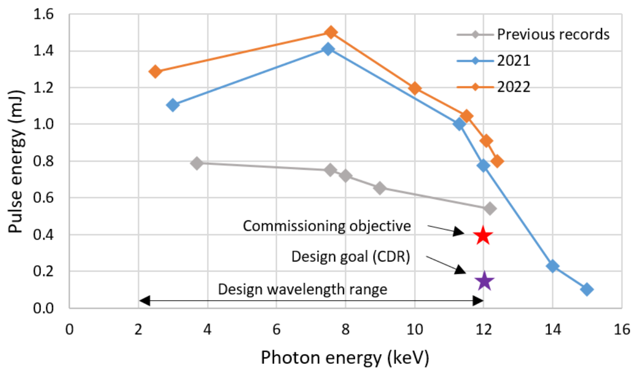
In 2022, the reliability of the machine could once again be improved significantly. Set-ups tend to be faster, with beam often available after one shift of set-up (three shifts per week are scheduled for the set-up), and the reproducibility of settings is improving. The operation crew can now prepare settings on Monday for the different beams requested during the week, reload semi-automatically these settings as needed during the week and restore peak performance with a minimum amount of manual tuning.

After the big step up in beam performance in 2021, the trend continued in 2022 with several new records established, e.g., 0.9 mJ at 12.1 keV and 1.5 mJ at 7.6 keV in Aramis, and 4.5 mJ at 400 eV in Athos. The present performances are approaching the predicted limits for our beam parameters in Aramis (about 1 mJ at 12 keV). A selection of beam performance records are shown in Figure 15.

What is even more important is that these excellent performance levels could be maintained throughout the year with beams in the mJ range in both branches for extended periods. The beam quality also improved with more control on the bandwidth and more stable beams in terms of intensity and pointing. The overall good performance is made possible thanks to systematic machine studies to improve our understanding of the machine and to the development of tools and procedures to further automatize operation.



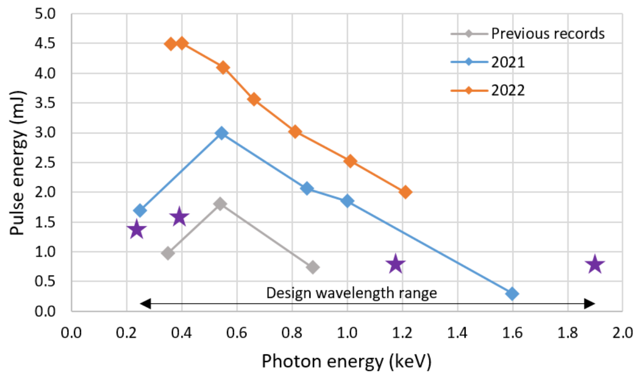


Figure 15: Evolution of the beam performances for Aramis (top) and Athos (bottom) in the last two years.

The main challenge of 2023 will be to operate the machine with three endstations in regular user operation and two more taking beam for commissioning and pilot experiments while maintaining peak performance. Furthermore, 2023 will see the first EEHG beams and more requests for advanced modes in Athos.

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