PAUL SCHERRER INSTITUT

# Operation of the PSI Accelerator Facilities in 2018

Antonio Barchetti, Joachim Grillenberger, Andreas Lüdeke, Thomas Schietinger, Marco Schippers, Daniela Kiselev

Division of Large Research Facilities, PSI

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

### High Intensity Proton Accelerator (HIPA)

In 2018, the operation of the High Intensity Proton Accelerator Facility started as scheduled on the 2nd of July after an extended shutdown period. The average availability in 2018 amounts to an excellent value of 94.8%, which corresponds to 40% less unscheduled downtime if compared to the year 2017.

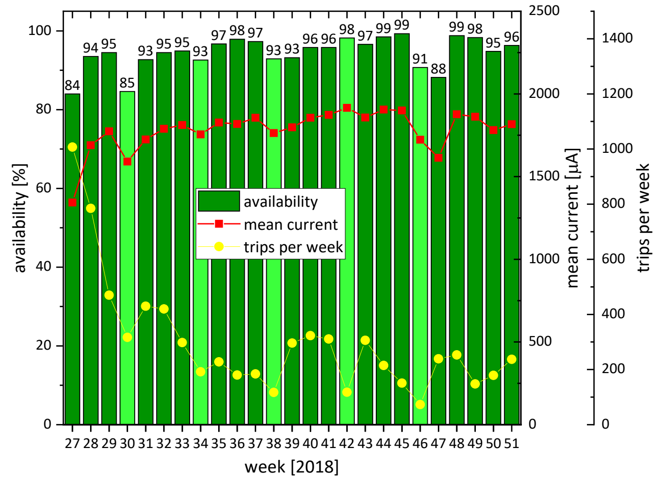


**Figure 1:** Green, weekly availability of HIPA in 2018 (light green denotes service periods). Red, average proton current on meson production targets. Yellow, total number of trips per week.

As mentioned, the year of operation 2018 was imprinted by an extended shutdown period of six months. The shutdown was prolonged in order to accommodate the time needed for the replacement of the old 150 MHz resonator 2 in the Injector 2 cyclotron with a new 50 MHz resonator. The final installation of the new resonator took place on the 20th of February as scheduled. After adapting the infrastructure to the new settings of Injector 2, the cyclotron was ready for beam production on the 9th of May.

However, the commissioning of RF-amplifier chain for this resonator is scheduled for 2019. Therefore, the Injector 2 cyclotron was operated in 2018 with three resonators only. This results in a lower gain of kinetic energy per turn (~40 keV) and thus a higher number of revolutions (86 instead of 82 turns) until the protons can be extracted from the cyclotron. This affects the quality of the extracted beam, which may in turn lead to higher losses in the Ring cyclotron. To keep the losses below an acceptable level, the beam current was therefore limited to a maximum value of 2 mA. Despite this fact, the maximum current onto the neutron spallation target SINQ was limited to 1350 µA (corresponds to 2 mA extracted from the cyclotron) to meet the provisions of the Swiss Federal Office of Public Health.

**Figure 2:** The new 50 MHz resonator installed in the Injector 2 cyclotron. The new resonator is capable of providing up to 400 kV/p accelerating voltage.

On May 9th, protons were extracted from the Injector 2 cyclotron at a current of 1 mA. Running the cyclotron with only three resonators required another eight days of beam development to finally achieve the desired beam current of 2 mA (onto BX2).

The commissioning of the Ring cyclotron was started on the 26th of June, whereby already on June 27th 1400 µA were sent to beam dump and the test beam sent to SINQ. The main issues we were facing arose from inverse polarization of a power supply, disturbances at some BPM readings as well as a not properly working beam probe (RRI2)

During the first week of operation (4 days only), an availability of 84% at a mean beam current of 1343 mA was achieved. This comparatively low availability was mainly caused by the high number of short interruptions (1007) observed during this week. Most of these trips were caused by discharges of the electrostatic elements EIC and EEC in the Ring cyclotron. These discharges usually occur after a shutdown since vacuum in the cyclotron is broken for several months. Also in the weeks 28 and 29, the electrostatic elements had to be conditioned several times due to the high number of discharges.

Fortunately, the number of short interruptions steadily decreased to 200 per week reaching the end of the operational period on the 21st of December.

After the relatively smooth operation during the weeks 28 and 29, the availability dropped from 94% to 85% in week 30. During this week, two days of service and two beam development shifts took place. Thus, outages have a higher relative impact on the availability due to a shorter run period. In this week, the longest interruption lasting three hours was caused by a problem with the system controlling the phase collimator KIP2 in the Injector 2 cyclotron. This system had to be power reset and calibrate again.
From week 31 on, the availability continuously increased to reach the years' highest value of 99.3% in week 45. Only minor incidents like water cooling problems in week 35 or PSYS/Radiation protection connected issues in week 39 affected the availability. During week 46, interlocks unnecessarily forced the microwave amplifier of the ECR-ion source to switch off. Usually, an interlock, e.g., triggered by a discharge of an electrostatic element, should initially activate the magnet AVKI to bend the beam onto a stopper right after the ion source. The ion source is switched off only in case the magnet fails. It turned out, that a damaged diode prevented the magnets ready signal to be passed to the interlock system, while the magnet AVKI was working all the time.
In week 47 the 10 kW amplifier stage of the Ring cyclotrons' cavity 4 failed. It was found that a damaged cable caused the outage. For unknown reasons this affected the magnet field distribution in the Ring cyclotron, so that the main magnets of the Ring cyclotron had to be cycled though they were not switched off during the repair. Trouble-shooting and repair, cycling the main Ring magnets and the subsequent setup of the accelerators affected the availability with nine hours.

**Table 1:** Operational statistics of the HIPA Facility

| **Beam-time statistics for HIPA** | **2018** |
|---|---|
| **Total scheduled user beam time** | 3681 h |
| **Beam current integral**<br>• to meson production targets<br>• to SINQ<br>• to UCN<br>• to isotope production targets | <br>6.64 Ah<br>4.37 Ah<br>0.049 Ah<br>0.004 Ah |
| **Outages** (current < 1 mA)<br>• total time<br>• total number of outages (t > 5 min)<br>• total number of trips (t < 5 min) | <br>191.4h<br>132<br>7460 |
| **Availability** | 94.8% |

Figure 3 characterizes the downtimes during the scheduled user operations by category of accelerator outages that lasted longer than five minutes. In total only 132 were registered in 2018. The distribution of outages differs significantly from the previous years.

The major contributions this year are related to problems with the control system (21.6%), water-cooling issues (13.6%), difficulties in setting up the accelerators (11.3%), RF related (9.1%) and PSYS related outages (8.0%).
One important aspect is the high reliability of the meson production targets in 2018 compared to the past years. In case of an outage of the target wheels, an exchange typically leads to two days of beam interruption and thus diminishing the contribution of other failure causes in the statistics.
It is worth mentioning, that the run period comprised only six months in 2018 and that the beam current of 1780 μA was comparatively low.

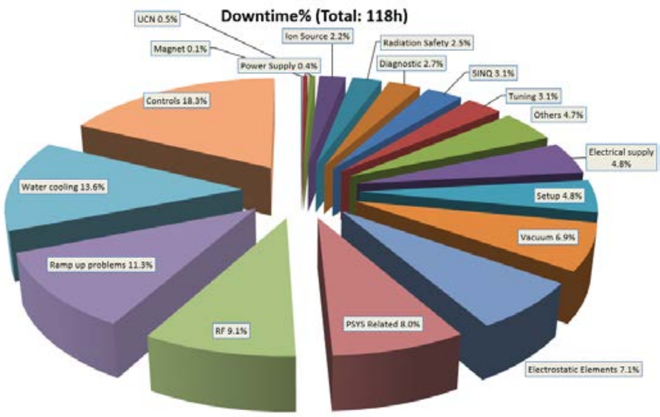


**Figure 3:** Outage characteristics at HIPA in 2018

In 2016, a water leak was detected in the vicinity of the beam dump which only occurred at currents above 1 mA. By modifying the beam shape during machine development shifts, the first of the four sectors of the beam dump was identified to be the most likely candidate leaking cooling water. Therefore, the first sector was replaced during the shutdown. After the exchange, no increase in vacuum pressure was detected when the beam was sent onto the beam dump with currents of up to 1.62 mA extracted from the Ring cyclotron.
For the ongoing upgrade of the Injector 2 again an extended shutdown of 6 months duration is scheduled for 2019. However, the installation of the second 50 MHz Resonator 4 is postponed to 2020. Test runs with this resonator revealed that up to 20 kW RF-power is dissipated in the resonator, most likely due to multipactoring effects. Nevertheless, most of the labor-intensive work, i.e., adaption of the infrastructure, preparation of insertion devices and septum magnets will be performed in 2019. Since the commissioning of the new resonator 2 is expected to be successful, four resonators will be available for the operation of Injector 2 in 2019. In case the commissioning of the new RF-amplifier chain is delayed, still three resonators are available as

during last year. Due to the shutdown of the neutron spallation source the beam will be sent onto the beam dump in 2019. Therefore, the beam current will be limited to max. 2 mA with 60 mm Target E.

### Swiss Light Source

The last year resulted in a beam availability of 99.1% the second best in the history of the SLS, just after 2016. Both, the Mean Time Between Failures (MTBF) at 114 hours and the Mean Time Between Distortions (MTBD) at 59 hours, prove an excellent year for the SLS.

Only one downtime in 2018 was longer than five hours, which was a combination of two events. A flow-switch at the frontend (X06DA-FE-DI1) caused an interlock. The water-cooling expert needed tunnel access to increase the water flow. Afterwards the RF stations A3 and A4 had difficulties to start-up again; an RF expert on-call had to come in to fix the problem. After 5 hours and 52 minutes beam was restored and experiments could continue.

Water flow interlocks made up a large fraction of the downtime last year (see Fig. 4). The events occurred in the first three weeks of operation, after the January Shutdown. A contamination of the water circuit was ruled out after measurements, and we eventually found the needle valves to be the root of the problem. During the shutdown, there must have been a short reversal of the pressure in the water-cooling circuit. That brief event caused all needle-valve heads to move a little bit. Consequently, the flow controlled by the needle valves changed slightly; since some flow interlocks have tight limits, even these small changes significantly increased the risk of water flow interlocks. The movable head of a needle valve is only required to block the flow completely. This feature is not used in the SLS; we only use the needle valves to control the flow. To prevent similar problems in the future, we fixated the heads of all needle valves with soldering points.

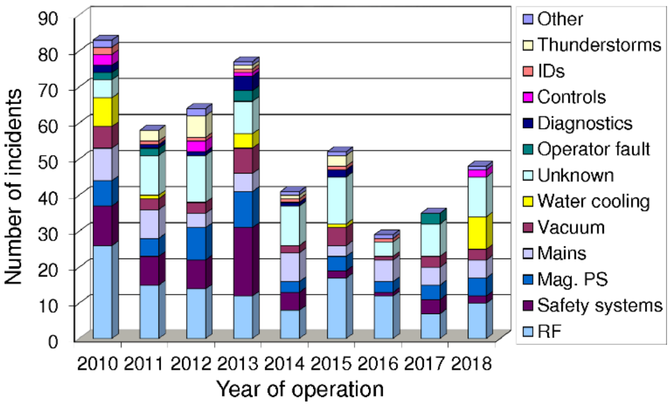


**Figure 4:** Beam outage count per system for the SLS

Figure 4 shows which subsystems caused beam outages in the past years. The water cooling problems described above were significantly contributing to the total number of trips last year. The number of beam trips for unknown reasons remains at a constant level.

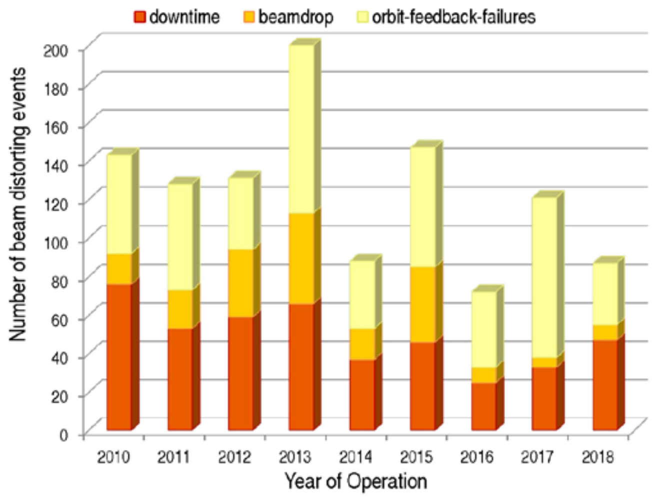


**Figure 5:** Number of beam distortions at the SLS

Figure 5 shows the count for different beam distortions in the past years. While the number of beam outages increased compared to the two last years, the number of orbit feedback failures reduced. This is in part due to the increased effort, which was put into the maintenance of the old BPM system in 2017. A sufficient number of well-tested spare electronics allowed for a timely replacement of sporadically failing BPMs and therefore reduced the overall number of orbit feedback failures.

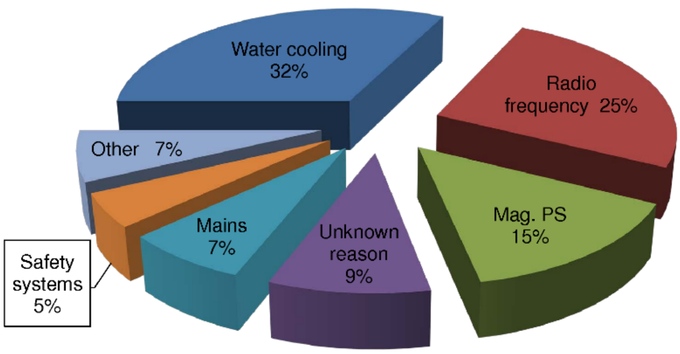


**Figure 6:** Beam outages per failure category for the SLS

Figure 6 shows the percentage of the beam outages attributed to the different failure categories. Since the water flow interlocks required many tunnel accesses to increase the water flow locally, these events had a rather long duration and contributed to a third of the SLS downtime in 2018. Table 2 shows the operation statistics of the past two years.

Table 1: SLS Operation Statistics

| Beam Time Statistics | 2018 | | 2017 | |
|---|---|---|---|---|
| **Total beam time** | 6824 h | 77.9% | 6784 h | 77.4% |
| • user operation | 5144 h | 58.7% | 5048 h | 57.6% |
| - incl. compensation time | 160 h | 1.8% | 184 h | 2.1% |
| • beamline commissioning | 840 h | 9.6% | 792 h | 9.0% |
| • setup + beam development | 840 h | 9.6% | 944 h | 10.8% |
| **Shutdown** | 1936 h | 22.1% | 1976 h | 22.9% |
| **User operation downtimes** | 44 | | 30 | |
| • unscheduled outage duration | 49 h | 0.9% | 63 h | 1.3% |
| • injector outage (non top-up) | 3 h | 0.1% | 1 h | 0.0% |
| **Total beam integral** | 2560 Ah | | 2528 Ah | |
| **Availability** | 99.1% | | 98.7% | |
| Availability after Compensation | 102.2% | | 102.5% | |
| **MTBF** (mean time between fail.) | 114 h | | 163 h | |
| **MTTR** (mean time to recover) | 1.1 h | | 2.1 h | |
| **MTBD** (mean time between distortions) | 59 h | | 42 h | |

## PROSCAN

In 2018 the cyclotron and beam lines for the proton therapy facility PROSCAN at PSI have been operating with an uptime of more than 7300 hours, which belongs to the years with the highest amount of uptime. The causes of the unscheduled downtime show a similar distribution as before. No components have contributed exceptionally or more than usual to the unscheduled downtime. As expected after the repair of the cryo-system in 2017, the problems and the repair in 2017 did not leave any remaining negative effect.

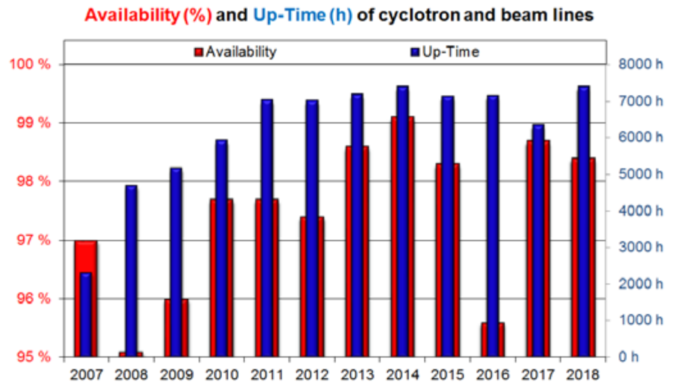


**Figure 7:** Availability and uptime for PROSCAN

Figure 7 uptime reflects the time that cyclotron and beam lines have been in the status "ready for beam delivery". Downtimes due to interlocks from the patient treatment side or due to commissioning activities at Gantry-3 have thus not been included in these statistics. The availability was 98.4%. Most interruptions took only a short time. Approximately 60% of the unscheduled interrupts due to RF or ion source interlocks took less than only two minutes.

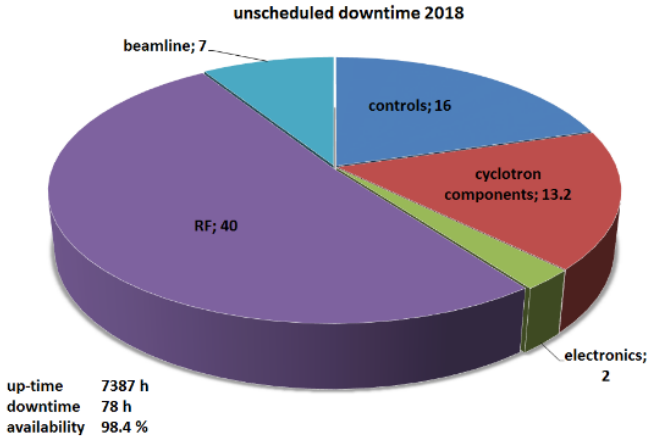


**Figure 8:** Distribution of unscheduled downtime at PROSCAN

A severe problem in the operation, but not visible in the availability, is the time requested by CPT for optimization of the beam quality from the cyclotron. Since a few years, the phase measurement in the beam extracted from COMET is being distorted due to electronic interference from the RF and surrounding power supplies. Therefore, this was unacceptable for a continuous control of the fine corrections to the magnet current of COMET. Therefore several times a day a resonance curve (= extracted beam intensity as a function of magnet current) has to be measured, to readjust the magnet current to the newly found optimum value. A better shielding of the phase measurement devices is a project of high priority in 2019.

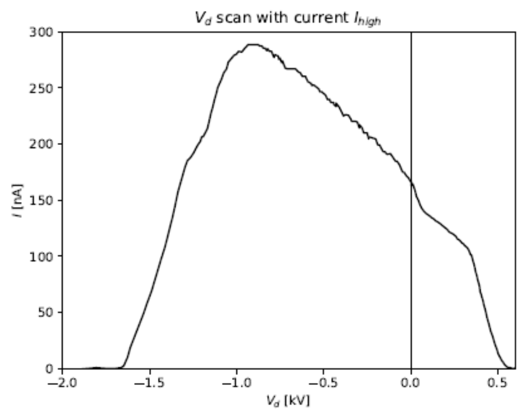


**Figure 9:** Intensity of extracted beam from COMET as a function of Vd, the voltage over the vertical deflector plate. In a symmetric situation the maximum should be at Vd = 0 kV.

Figure 9 shows an asymmetry in the extracted beam intensity as a function of the vertical deflector voltage polarity. This asymmetry is giving problems in the beam intensity control performed in the continuous scanning program running at Gantry-2.

Simulations have been performed regarding the beam position in the central region of COMET. In the simulations, a vertical displacement of the chimney hole of the ion source was compared with a vertical displacement of the vertical collimator. Figure 10 shows such simulations of the beam in the central region of COMET.

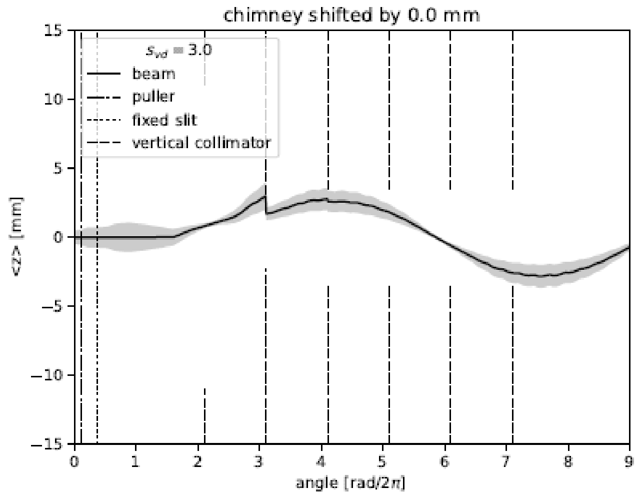


**Figure 10:** The beam in the vertical plane in the center of COMET when vertically deflected. It will be stopped partially during its five crossings of the vertical collimator; here for a centered chimney.

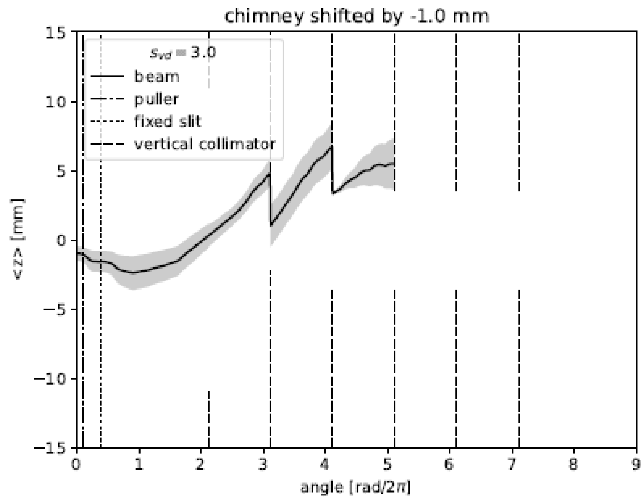


**Figure 11:** Same as above, here for a chimney offset of -1 mm.

The simulations have shown that a vertical shift of the chimney gives the most effect on the asymmetry. Therefore, in 2019 we plan to do experiments in COMET with different vertical positions of the ion source chimney hole, to find a position that yields more symmetry. A set of dedicated (=asymmetric) chimneys are being made for these tests.

**SwissFEL**

During 2018, SwissFEL continued and completed the pilot phase of the Aramis hard X-ray beamline, adding another eight experiments to the two pioneering experiments from 2017 for a total of ten experiments within this pilot phase. As new RF stations became available for acceleration in the Linac, higher and higher electron energies could be reached during the pilot phase, thereby gradually raising the photon energy available to the users. The repetition rate in regular operation was increased from 10 Hz to 25 Hz, with one experiment using 50 Hz and some tests at the nominal 100 Hz. In parallel to the Aramis experimental programme, preparation and installation work on the second beamline, called Athos and dedicated to soft X-rays, proceeded throughout the year. After a one-month shutdown in January, SwissFEL operated with 11 C-band RF stations (eight in Linac-1, three in Linac-3), providing beam energies up to 2.7 GeV for the following measurement period. The first few weeks in February were dedicated to machine studies with the goal of further optimizing the FEL performance. To this end, the second RF deflector was commissioned and subsequently used to verify the electron bunch length at the end of Linac-3. The improved FEL beam was then utilized for the commissioning of photon diagnostics and timing tools in view of two further pilot experiments scheduled in March. The experiments at the Alvra and Bernina endstations were carried out at still relatively modest photon energies of 2.2 keV and 2.0 keV, respectively, and a repetition rate of 10 Hz.

During a three-week shutdown in April, more RF stations were connected to the beam pipe, initially enabling beam energies up to 3 GeV with 13 Linac RF stations online. Around the same time, first tests with repetition rates exceeding 10 Hz were performed. By mid-May four more RF stations became available, raising the attainable electron beam energy to 4.35 GeV. The higher beam energy was used for a dedicated radiation dose mapping at 25 Hz. Further machine development work included first beam tests, in the injector, of the two-bunch operation mode as it will be required later for the simultaneous operation of the Aramis and Athos beamlines. On the photon side, the beam energy was tuned to 3 keV for the following pilot experiment at the Bernina endstation. An electron beam energy of 3.5 GeV was sufficient to reach photon pulse energies in excess of 500 µJ. Furthermore, this experiment was the first to run at a repetition rate of 25 Hz, revealing numerous challenges associated with data acquisition at higher rates. For the ensuing Alvra experiment at the beginning of July Aramis delivered 5 keV photons (electron energy 4.2 GeV) at a repetition rate of 50 Hz, which could only partially be used by the experiment. After that, the electron energy was further increased to 4.8 GeV to provide up to 8 keV photon energy for the upcoming experiments. Two more pilot experiments were carried out before the summer shutdown, one at the Bernina endstation (6.9 keV, 10 Hz) and one at the Alvra endstation (4.5 and 6.0 keV, 25 Hz). Measurements of the latter experiment were based on the serial femtosecond crystallography (SFX) technique and constituted the first biology experiment performed at SwissFEL.

The summer shutdown from mid-August to mid-September was primarily used for installation work on the Athos beamline. During the machine development time after the shutdown the Athos project reached an important milestone: for the first time, electrons were sent down the Athos beamline up to the beam stopper in front of the undulator line (the latter still to be built). Also in the weeks after the shutdown, all remaining RF stations of the Linac were put into operation (with one exception in Linac-2), pushing the available electron beam energy close to 6 GeV, well beyond the nominal 5.8 GeV. For the following photon delivery period, however, the electron energy was set to 5.3 GeV. The run culminated in another pilot experiment carried out at the Bernina endstation with photon energy tuned to 8.7 keV. The repetition rate was kept at 25 Hz to give the experiments more time to address the data acquisition issues at higher rates. To gain more system experience on the machine side, however, SwissFEL operated at 100 Hz during a brief test run after the completion of the experiment.

SwissFEL was again in a scheduled shutdown for three weeks in November. Another biology experiment, carried out in December at the Alvra endstation, marked the completion of the SwissFEL Aramis pilot run. Stable delivery of 9 keV photons at 25 Hz, with photon pulse energies in the 500–600 µJ range, bode well for the first user run starting in early 2019! At the same time, the Athos beamline is well on track for first lasing before the end of 2019.