Operation of the PSI Accelerator Facilities in 2020

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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)

The availability of the High Intensity Proton Accelerator Facility amounts to 88.9% at an average beam current of 1670 μA. Initially, the start of the operation was scheduled for 18 May 2020. However , the shutdown was interrupted on 16 March 2020 due to the COVID-19 pandemic. After a detailed re-planning considering protection concepts given by the authorities and PSI's pandemic staff, the shutdown continued on 28 April whereas the new date for the start of the user operation was schedule for 13 July. Only thanks to the commitment and expertise of the involved groups, the projected end of the shutdown was delayed by only 2 weeks and the accelerators were ready for setup as planned.

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

Beam-time statistics for HIPA	**2020**
Total scheduled user beam time	2936 h
Beam current integral total (during user operation)	
• to meson production targets	5.26 (4.84) Ah
• to SINQ	3.39 (3.26) Ah
• to UCN	0.031 Ah
• to isotope production targets	0.007 Ah
Outages (current < 1 mA)	
• total time	325 h
• total number and time of long outages (t > 5 min)	188, 276 h
• total number of trips (t < 5 min)	454, 49 h
Average beam current	1636 mA
Availability	88.9%

Unfortunately, the already commissioned Cockcroft-Walton pre-accelerator kept failing due to problems with the acrylic glass tube surrounding the acceleration section. As a consequence of many discharges and air inside the tube, a conductive layer had formed (Fig. 1) preventing high-voltage operation. Since a replacement of the tube would have taken up to 4 weeks, it was decided to remove the contaminated layer by polishing the inner surface of the existing tube. After the repair and the re-conditioning of the high-voltage, the Cockcroft-Walton was ready for beam on 13 July.After only two days of commissioning of the Ring cyclotron a beam current of 500 μA was extracted and sent onto the beam dump.

On 20 July, a 10-day test program of the Neutron Spallation Source SINQ commenced to study the performance of the facility after the upgrade of the neutron guides in 2019. After completion, regular user operation started on 1 August 2020.

Figure 1: Acrylic glass tube surrounding the acceleration section of the Cockcroft-Walton. The visible brownish "bloom", formed a conductive layer of 100 MΩ instead of the required 50 GΩ.

During the first week of user operation, a beam current of 1300 μA was reached as scheduled. However, the availability was affected by a total of 21 hours of outage time (Control, RF, Cooling), reaching 84%.

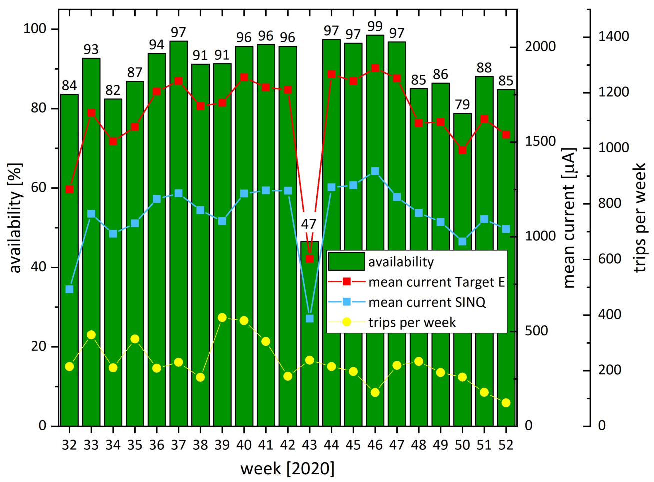

Figure 1: weekly availability of the High Intensity Proton Accelerator facility in 2020

In the second week of operation, an availability of 93% of the facility was achieved. In week 34 the availability was affected by a damaged vacuum gauge in the high-energy beamline (1.5 h) and the outage of resonator 4 due to a faulty relay (1.9 h).

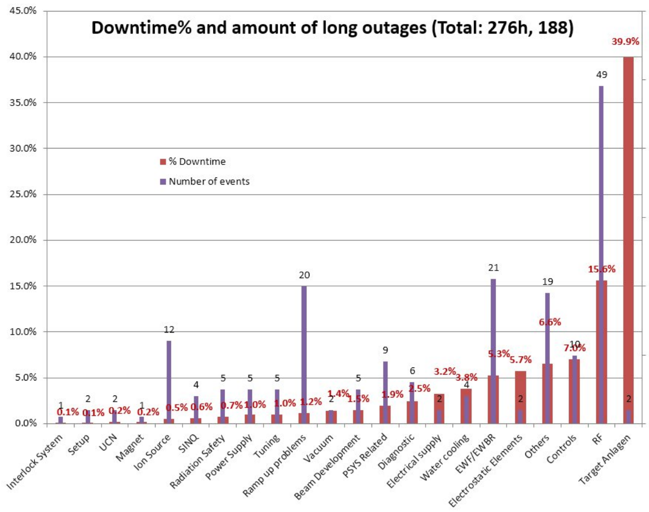

Figure 2: long outage (t>5m) characteristics of the High Intensity Proton Accelerator facility in 2020

Two outages of cavity 3 (3.5 and 6.8h) in week 35 were caused by a short circuit of an RF-tube driving the 1 kW stage. Furthermore, a crowbar ignition led to an outage of cavity 2 (2 h) just one day later. Correspondingly, the availability in week 35 amounts to 87%. During the subsequent seven weeks, a smooth operation of the facility with availabilities of up to 97% was observed. Unfortunately, target E failed on 17 October due to a damaged ball bearing resulting in an availability of only 47%.

In weeks 48 and 49, we experienced problems with the stability of the high voltage in the Cockcroft-Walton pre-accelerator. The troubleshooting was difficult since obvious reason for discharges was found. It turned out that oil in the pressurized air system caused dark currents and thus a frequent shut down of the high voltage. Replacing air pipes and removing oil from affected components mitigated the problems. The reason for the oil in the air system is currently under investigation.

In the week before last of user operation, target E failed again and had to be replaced. As the target was replaced overnight, however, the impact on the availability was comparatively low.

For 2021, the directorate of PSI requested an extended run period of at least eight months. To meet this request, the start of the user operation is scheduled to 12 April 2021. Since the replacement of resonator 4 in Injector 2 was postponed, a relatively short shutdown of 3.5 months is manageable.

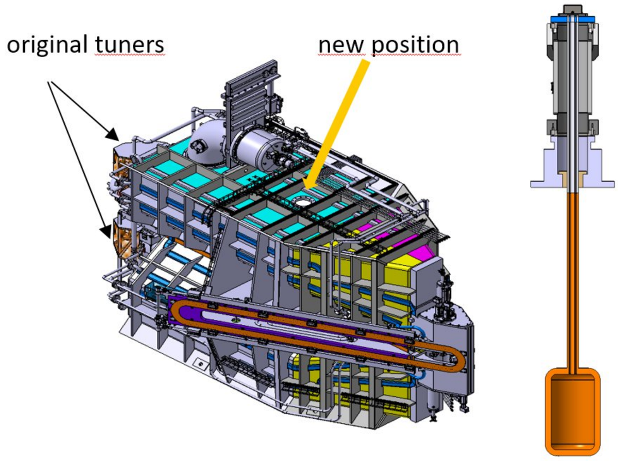

Figure 3: right, draft design of a new tuner without finger contacts. The movable displacer will extend 1 m into the resonator to tune the resonance frequency within a range of 200 kHz. It will be installed in a new position in addition to the original tuners.

Concerning the Injector 2 upgrade, a new conceptual design of a tuner without finger contacts has been created. First tests with the new tuner are expected for the last quarter of 2021. The final installation is foreseen for 2022. In this case, beam currents of up to 2.2 mA are again feasible.

Swiss Light Source (SLS)

The beam availability in 2020 was 98%.The mean time between failures (MTBF) was 116 hours, an excellent value; but the mean time between distortions (MTBD) was just 26 hours, the lowest value of the past six years.

The main incident of the year was not related to the accelerator: due to the COVID-19 pandemic external users could not travel to PSI between mid of March and June. At the same time PSI wanted to offer their beamlines for a COVID-19 priority call, to deepen our understanding of the virus. For all other experiments users were just sending in their samples and the beamline staff was performing the experiments. Due to the limited internal staff a 7-day operation was not feasible. As a compromise we switched the SLS to 5-day operation: start-up on Mondays at 6am, stable 400 mA for beamlines starting at 3pm on Mondays and user operation from Tuesdays 3pm to Saturdays 5am. After the shutdown end of May we switched back to 7-day operation per week.

In week 3 a ceramic window broke in the 3 GHz RF waveguide in the Linac and subsequently caused 30% of the downtime in 2020. After the replacement of the window it had to be RF conditioned to power; in total this incident caused 26 hours of beam outage.

About three weeks later a power outage caused problems again at the Linac, the RF power had to be reduced and a new setting for the Linac had to be found in order to continue operation.

A water leak at a cavity in week 14 caused another five hour downtime, until it could be provisionally fixed. This was a very troubling incident, since the cavities had been replaced about five years ago: the first generation of cavities had many water leaks from cavitation. For the new cavities we reduced the water flow and carefully tuned the flow not to cause cavitation. We would have not expected any leaks to occur after just five years.

An eight hour outage was caused in week 41 by a problem with the filament heater at ARIRF-A4. Large noise on the readback caused interlock trips. This problem caused a total of six outages over one weekend, summing up to nearly 19 hours of downtime. Several connectors were replaced and the cabling was redone to overcome the problem.

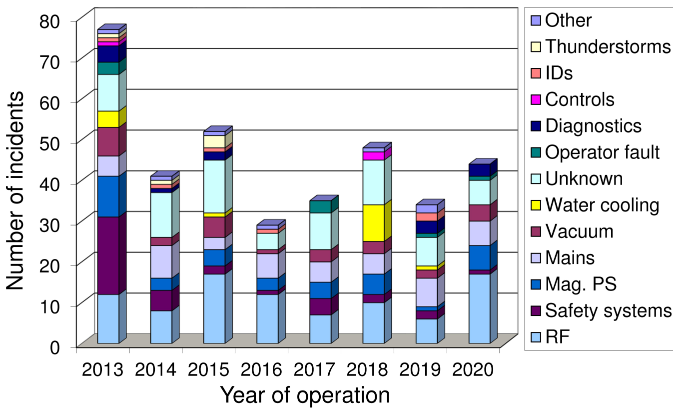

Figure 3: beam outage count per system for the SLS

Figure 3 shows the number of beam outages for each system. About 40% of all outages were caused by the RF this year. The total number of beam outages was still low, and the mean time between failures was very good with 116 hours.

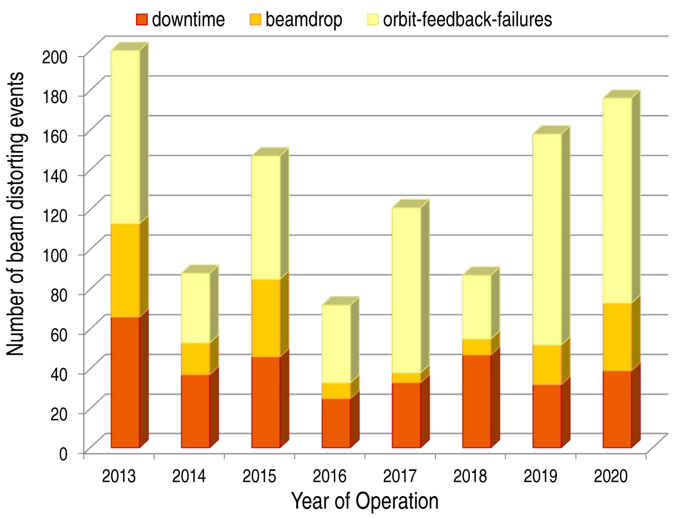

Figure 4: Number of beam distortions at the SLS

Figure 4 shows number of beam distortions in 2020. The orbit feedback outages remained on a high level and the number of incidents at the Linac was slightly increased compared to recent years.

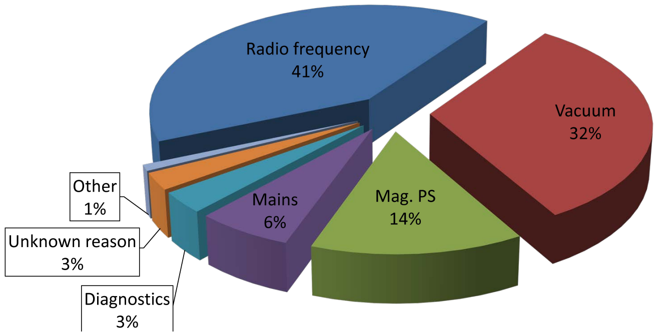

Figure 5: Beam outages per failure category at the SLS

Figure 5 shows the relative contribution of the different systems to the total downtime. RF and Vacuum were dominating the downtime. Most of the vacuum outage time could have been attributed to the RF as well, since the bad vacuum was caused by a broken RF window at the Linac. Otherwise the systems were operating stable.

The problems with the magnet power supplies were mostly caused by one device: the main dipole PS in the storage ring. After maintenance the device switched off every other day. The reported failure was not helpful to locate the problem: some resistors were overheating and causing other circuits to malfunction.

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	2020	2019
Total beam time	6316 h 71.9%	6736 h 76.9%
• user operation	4652 h 53.0%	5056 h 57.7%
- incl. compensation time	144 h 1.6%	160 h 1.8%
• beamline commissioning	760 h 8.7%	860 h 9.7%
• setup + beam development	904 h 10.3%	920 h 10.5%
Shutdown	2468 h 28.1%	2024 h 23.1%
User operation downtimes	39	32
• unscheduled outage duration	96 h 2.0%	42 h 0.8%
• injector outage (non top-up)	26 h 0.6%	6 h 0.1%
Total beam integral	2315 Ah	2512 Ah
Availability	98.0%	99.2%
Availability after Compensation	101.1%	102.4%
MTBF (mean time between fail.)	116 h	153 h
MTTR (mean time to recover)	2.5 h	1.3 h
MTBD (mean time bet. distortions)	26 h	31 h

The average beam lifetime was about two hours higher in 2020 than in previous years. This was achieved with a new filling pattern, proposed by M. Aiba: 430 out of 480 buckets were filled in the storage ring, leading to lower peak charge and a more even bunch lengthening by the 3rd harmonic cavity, both causing a longer lifetime. [1]

PROSCAN

In 2020 the cyclotron and beam lines for the proton therapy facility PROSCAN at PSI have again been operating with an uptime of more than 7100 hours.

The shown uptime in Fig. 6 reflects the time that cyclotron and beam lines 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 98.7%.

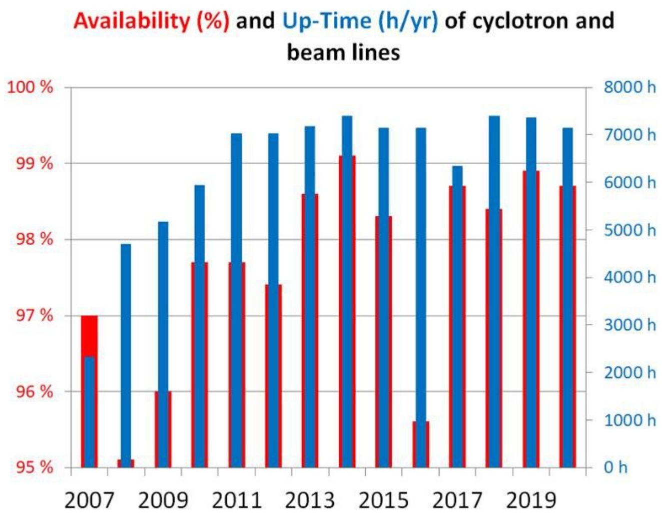

Figure 6: Operating hours per year and availability of PROSCAN.

The causes of the unscheduled downtime are shown in Fig. 7. There were no specific components that have given major problems. Due to replacements and upgrades of electronics and control some extra time was needed for commissioning. Also in 2020 some time has been lost due to problems in the beam lines, mostly related to interlocks in Gantry 3. These were caused by problems in beam alignment in the gantry and/or at the gantry’s coupling point.

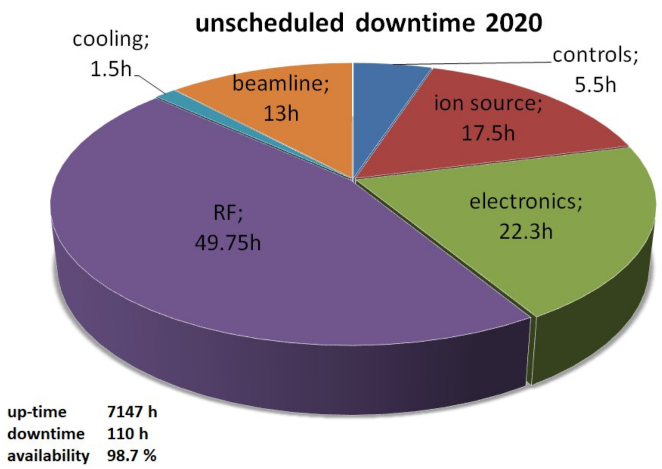

Figure 7: The unscheduled downtime by causes.

Despite the partially successful effort to improve the stability of the beam transport to the gantry, many problems related to these interlocks have not been understood yet, since the Gantry 3 control system is not able to provide us the relevant time-stamped data. This is in development together with the supplier Varian. The phase measurement has been rebuilt and is now based on the detection of a 216 MHz signal from the beam, which is the third harmonic of the 72 MHz RF signal. This is much less sensitive to interference from the RF and other sources. Experiments have shown that it can work down to an intensity of 5 nA from the cyclotron. Also the feedback system of the phase measurement to the power supply of the cyclotron magnet current has been adapted and an EPICS-app has been implemented in the control system. After a test period the system will be used routinely and we expect a reduction of the number of long beam interruptions for manual retuning of COMET.

In a study of the centre of the cyclotron, experiments and simulations have been performed to investigate the effect of a shift of the puller towards the ion source. We investigated the effect of a combination of this shift of the nose of the first Dee (i.e. the puller) with a rotation of the ion source chimney. Simulations with OPAL have shown that a shift of 0.57 mm and a 5.6 degree rotation will yield a transmission improvement between the ion source and the first turns behind the first (fixed) phase slit. An experiment in the cyclotron centre, has indicated a transmission increase of a factor 2.5. Next steps in the project will be aimed at optimization of the Dee voltage and the phase slit. With these optimized settings we expect to improve the beam centring to enable acceleration and extraction from the cyclotron. Such a centring adjustment is needed, since the beam will enter the central region under different conditions. If this is successful, we have to investigate the optimal benefit from this modification: either more beam extracted from the cyclotron or a reduction of the arc current in the ion source, to obtain the same extracted beam intensity with a more relaxed source setting. This last option will yield much longer time intervals between source services, as well as a lower production of activation in the cyclotron.

Since February 2020 FLASH experiments are performed in collaboration with CPT. The so called Flash effect is a possible reduction in in healthy tissue complication if the irradiation is performed with an approximately 1000 times higher dose rate than normally used in treatments. In these experiments 250 MeV beam pulses of 800 nA during few milliseconds, are transported to the Gantry 1 treatment site, to irradiate biological samples. The number of pulses has been limited by the officially allowed maximum charge per hour. In order to enable the gantry magnets to transport this beam energy, the gantry’s power supplies have been modified to provide a higher magnet current. First tests with the recently developed non-interceptive beam intensity monitor, based on a resonating cavity, have shown its advantages of not intercepting the high intensity beam and a non-saturated signal that is measuring the beam intensity with specified accuracy within these short pulses. This makes monitors based on this principle, very interesting candidates to control the FLASH experiments at PSI.

SwissFEL

Despite the pandemic crisis, 2020 saw large progress with the installation and commissioning of Athos. The first photon beam reached the Athos end stations (Maloja) in June and parallel operation was achieved for the first time with 100 Hz repetition rate on both branches in September. The user operation programme on Aramis was affected by the pandemic crisis. Nevertheless, a large part of the user operation programme could be maintained.

The scheduled user experiment programme was largely disrupted in spring. The machine was stopped on the 17th of March and the spring shutdown was extended until 27th of April. The machine could be restarted in May, with a minimum of personnel on-site and experts connecting remotely. Until end of May, machine operation was restricted to weekdays with shutdowns during the weekends. From June, 24/7 operation could be resumed. The user operation programme was reshuffled to compensate for the lost shifts in spring. Despite the difficulties, 12 user experiments could be performed in 2020. A total of 176 shifts of user operation could be delivered, slightly less than 2019 (192). As in previous years, the time between user experiments was shared between experiment preparation and commissioning of photonics equipment on the one hand, and machine improvement and development on the other.

Figure 8 summarizes the beam availability during weeks dedicated to photon delivery. Scheduled photon beam delivery (user operation and beamline development) in April and May could obviously not be delivered, leading to a poor averaged availability in 2020 (79.6%). However the beam availability outside this period was actually rather good (94.2%) compared to 2019 (85.7%). This is due to a lower number of large failures in 2020 and faster recovery times.

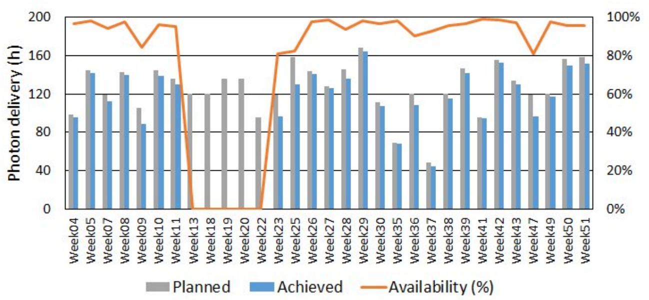

Figure 8: SwissFEL Aramis operation statistics during photon delivery weeks in 2020.

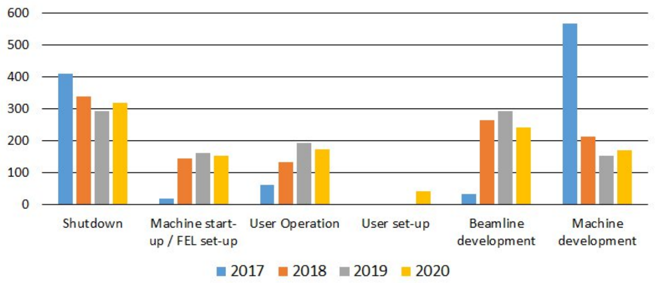

Figure 9: SwissFEL Aramis shift distribution 2017-2020.

The overall machine shift distribution (Aramis) was very similar to the two previous years with slightly less photon beam delivery and slightly more set-up shifts and shutdowns (see Fig. 9). This is of course directly related to the COVID-19 crisis and the operation restrictions during the first lock-down.

Like in previous years, four shutdowns took place during the year allowing access for maintenance, repair and installation work. Five short service days of four shifts each were also scheduled in between the shutdowns for periodic maintenance and Athos undulator installation. Major installation work took place in 2020. Most of the Athos line was completed with the installation of 12 of the 16 undulators of the Athos line, the installation of the C-band RF station and Athos dechirpers. The new Mizar laser was also installed and brought into operation, allowing for improved electron bunch quality for Athos.

In 2020, the nominal repetition rate could be achieved routinely for Aramis during user operation thanks to significant improvements in control systems and data acquisition. Previously data acquisition had difficulties to process experimental data at full rate, limiting the beam rate to 50 Hz during user operation. Machine start-ups after shutdowns got generally faster and more reliable in 2020 with good lasing level achieved within a few days of the start-up. The beam quality also improved with high lasing intensities achieved with narrow spectral bandwidth (0.1%) and improved timing jitter and photon pulse length (50 fs FWHM). During 2020 high photon pulse energies could be achieved (570 µJ at 12.0 keV, 620 µJ at 9 keV, 780 µJ at 7.5 keV) but also the reproducibility and stability of the machine improved.

In 2020 the first 2-bunch runs took place, with regular period of parallel beam delivery in Aramis and Athos. The acceleration of 2 bunches in the same RF pulse is a unique feature of SwissFEL. This could be demonstrated throughout 2020, even with nominal repetition rates of 100 Hz on both branches (September). Athos suffered from losses problems especially near the end of the year making it difficult to maintain high repetition rates. This could be mitigated by beam based alignment and progress in the electron beam set-up. Four pilot runs took place last year in Maloja (the first end station of Athos). The first beam in Maloja was achieved at the beginning of July (0.54 keV, 100 µJ) with six undulators.

Then three more Maloja runs took place until the end of the year. A record intensity could be achieved in September with 1.8 mJ at 0.54 keV. Unfortunately, the good performance could not be maintained and the last Maloja runs suffered from poor beam quality and losses in the Athos lines limiting the repetition rate.

With Athos coming on-line the reproducibility and efficiency of the electron beam set-up after a shutdown of the facility has to be enhanced in order to guarantee optimal performances on both lines. In 2020 Athos operation was given priority over Aramis during certain weeks to ensure the pilot runs could take place as it was still challenging to achieve simultaneously good lasing on both branches. Improving the setup procedures is the focus of current activities and will be crucial to achieve reliable operation of the facility.

A large fraction of the machine development work was dedicated to the commissioning of Athos and to establish 2-bunch operation. In particular a new RF scheme was developed to provide independent tuning in amplitude and phase for the second bunch. This is achieved with a small step in amplitude and phase of the RF pulse in the S-band Linac and first C-band Linac affecting only the second bunch. Although the tuning range is limited, this gives the possibility to correct for small differences in energy and compression of the two bunches. The timing and event system was upgraded to allow independent control of the repetition rate of the two bunches and to decouple them in the machine protection system and in the different diagnostics. The feedback system was extended to control bunch 2 parameters in particular orbit and energy.

Beside Athos commissioning work, a large part of the machine development shifts was dedicated to establishing special modes of operation beyond the standard SASE mode. Among them spatially chirped FEL pulses providing pulses with variable photon energies along a transverse direction, could be achieved and used in a test experiment. The use of corrugated structures to streak the electron beam transversally was also pioneered in Aramis. With this technique, the temporal profile of the FEL beam could be reconstructed with a passive structure.

The goal for 2021 is to achieve reliable parallel operation and to improve reproducibility of the machine. With Athos starting regular user operation, optimal performance on both branches should be achieved routinely. The 2021 planning will see an increase of user operation and beamline development shifts on Aramis. Six pilot experiments and friendly user runs are scheduled for Athos. 2021 will also see the first light in Furka (the second end station of Athos) and Cristallina (the third end station in Aramis). Finally, some initial work was launched in 2020 towards a proposal for a third FEL line in SwissFEL named Porthos.

References

[1] M. Aiba et al., Exploring the Potential of the Swiss Light Source, Journal, in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1554-1556. doi:10.18429/JACoW-IPAC2019-TUPGW066