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Operation of the PSI Accelerator Facilities in 2019

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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)

In 2019, the operation of the High Intensity Proton Accelerator Facility HIPA started as scheduled on 2 July after an extended shutdown lasting six months. The average availability in 2019 amounts to 94.6% at an average beam current of 1583 μA (see Fig. 1 and Tab. 1).

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

Beam-time statistics for HIPA	**2019**
Total scheduled user beam time	3589 h
Beam current integral • to meson production targets • to SINQ • to UCN • to isotope production targets	 5.87 Ah -- -- 0.023 Ah 0.001 Ah
Outages (current < 1 mA) • total time • total number of outages (t > 5 min) • total number of trips (t < 5 min)	 193 h 93 4726
Average beam current	1583 μA
Availability	94.6%

Due to the ongoing upgrade of the neutron spallation source, i.e. the replacement of the neutron guides in sector 10 and the modification of several instruments and experimental areas, the 590 MeV beam was sent onto the beam dump. The beam current extracted from the Ring cyclotron was limited to approx. 1.85 mA during regular operation. Furthermore, the commissioning of the new Resonator 2 and the replacement of Resonator 4 in the Injector 2 cyclotron was postponed due to technical issues which are described in detail below.

Though the installation of the new Resonator 4 was postponed, the shutdown period was nonetheless extended to prepare the infrastructure for the upgrade of Injector 2.

The concrete bars forming the roof shielding of the Ring cyclotron bunker exhibited many damages, after 50 years of repeated crane handling. As a cost effective and sustainable solution, missing pieces of concrete were replaced and the edges were reinforced with steel profiles.

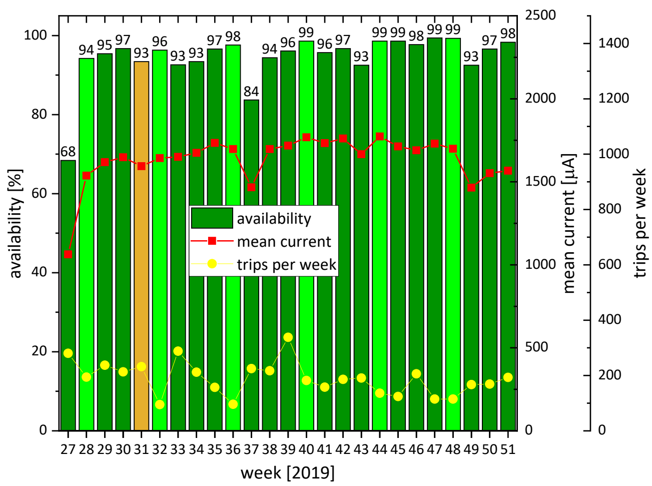

Figure 1: Green, weekly availability of the accelerator facility in 2019 (light green denotes service periods). Red, average proton current on meson production targets. Yellow, total number of trips per week.

Since the facility was operated without SINQ, a 60 mm thick Target E was installed to provide a high yield of mesons. For the first time, a special version of this rotating target was installed. Each of the twelve sector blades of the target wheel was engraved with grooves of different depth varying from 0.3 to 0.9 mm. Furthermore, the distance between these grooves was chosen differently on each side of the blades. The underlying idea of this concept is an additional diagnostics capability to detect discrepancies in the centring of the beam onto the target. With this configuration, a beam aligned slightly off-centre to the left/right of the target would lead to a signal modulation with a frequency of 114/138 Hz observed by the beam current monitor located after Target E.

From 25 November on, a new version of the Target E with an effective thickness of 40 mm was used. The surface of this so-called *slanted target* is hit by the beam at an angle of 8°. In that case, the incident beam passes through a larger surface, which leads to a meson production rate that is 30 to 60% higher depending on the secondary beamline setup. These values predicted by simulations were confirmed by measurements within an error of ±5%. Another benefit of this type of target is that the centring of the beam onto the target is less critical. Following these excellent results, the slanted Target E will also be used in 2020, provided it did not exhibit any damage.

Beam Time Characteristics 2019

The commissioning of the accelerators and the test measurements with the engraved targets were successfully performed during the last week of June. After the first day of user operation a forced software upgrade for the network analyser of the beam current monitor MHC5 took place on 3 July, Unfortunately, the upgrade led to a beam interruption of almost one day because of software driver incompatibilities.

After smooth operation during weeks 28 to 36, the availability dropped from 98% to 84% in week 37. The reasons were difficulties in setting up the accelerators after the service period and problems with the electronics of the transmission interlock system. In total five CAMAC crates were found to be damaged, most likely due to a short circuit. However, the reason why all crates failed almost simultaneously is still unclear. In fact, the traditional CAMAC system is currently being replaced with high priority since there are only few spare parts left after this incident.

On 20 October, a sparkover in the 15 kW transformer caused the Ring flattop cavity to fail. During the repair of the transformer, the 100 kW amplifier stage driving cavity 4 of the Ring cyclotron caused a cooling interlock due to a water leak. To reduce the downtime, the 100 kW amplifier stage of the Resonator test stand was seized as a substitute. In total, the repair lasted almost twelve hours.

During the final two running periods of 2019, the facility performed with an outstanding availability of over 98% on average. Only during week 49, the availability dropped to 93% due to a damaged pneumatic cylinder in the πE5 experimental area, which took seven hours to fix.

Corresponding to the miscellaneous reasons for downtimes and the respective time needed for troubleshooting, the operational statistics of the reporting period are dominated by diagnostics outages, the radio frequency system, and problems setting-up the accelerators (see Fig. 2). It is important to note that the total downtime caused by diagnostics outages is high if related to the number of diagnostics failures. The conservative electronic systems require special training for the new generation of staff. This and limited resources led to the long repair times.

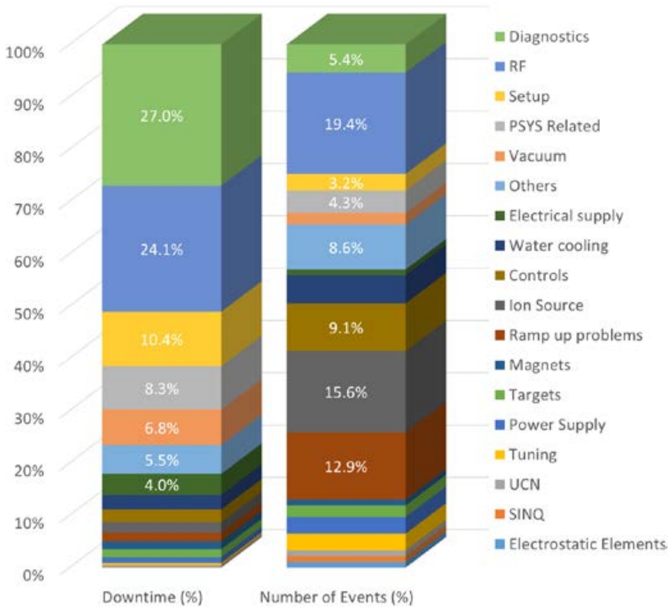

Figure 2: Downtime characteristics of the operational period 2019 by category. Shown are outages that lasted longer than five minutes. In total, only 94 were registered in 2019, which corresponds to a total downtime of 124 hours.

Status Injector 2 Upgrade

As mentioned in the Annual Report of 2018, the installation of the second 50 MHz Resonator 4 was scheduled for the shutdown 2020. However, after several improvements of the RF system, e.g. the cooling, still up to 20 kW RF power was dissipated in the resonator [1]. Therefore, it was finally decided to treat the inner surface (bottom only) of the resonator with AQUADAG to suppress multipactoring effects. Indeed, this step led to a significant improvement and the undesired multipactoring could be reduced to an acceptable level. Unfortunately, the mechanical tuning system consisting of a plunger and finger contacts still exhibited problems. For tuning the resonance frequency plungers are installed in the resonators. These plungers are permanently shifted by a hydraulic system by up to 200 mm with gold coated finger contacts that surround the plungers for the RF current to flow towards the cavity wall.

After one month of tests, abrasion of the silver graphite contact material and discharges were observed which may lead to dust in the cavity and scratches in the gold plated copper of the plunger. This is not acceptable for the operation in the cyclotron. Until now, different materials and contact types have been tested, but no satisfactory results have been found, which leads to another year of delay of the project. The optimal solution would be a complete re-design of the tuner without finger contacts. Due to lack of manpower, it is unclear whether this concept can be realized within 2020 to be able to install technically mature tuners and to commission both new resonators for operation in 2021.

Future Upgrades and Outlook

Throughout August, a strong increase of Röntgen radiation caused by multipactoring in cavity 5 of the Ring cyclotron was observed (see Fig. 3). This well-known effect occurs if the graphite coating supressing secondary electron emission depletes.

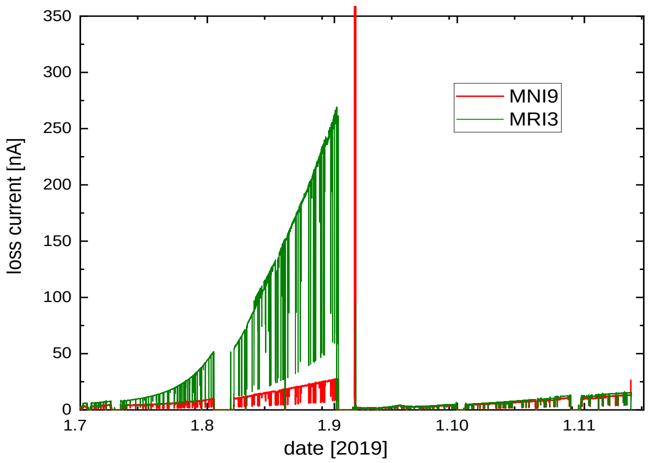

Figure 3: Röntgen radiation detected by the loss monitors MNI9 (red) and MRI13 (green) in the Ring cyclotron. After the treatment with AQUADAG the radiation level clearly diminished.

Since beam loss monitors detect this Röntgen radiation, the signal caused by the true proton losses is superimposed. This is a critical issue because a distinction between proton losses and X-rays is not possible. Due to the apparent exponential growth of the radiation level, a new layer of AQUADAG was applied to the inner surface of the flattop cavity during the service period of week 36, as a precaution.

After the treatment, the radiation measured by the beam loss monitors returned to a reasonably low level of 5 nA. Although there was no impact on the availability of the facility, it is obvious that cavity 5 is degrading at an increasing rate after more than 40 years of operation. In the forthcoming years, it may be necessary to treat the cavity with AQUADAG at least once a year, which would lead to a higher personal radiation dose for the staff. For a reliable operation during the next decades and less personal radiation dose, replacing the cavity is mandatory. A more powerful flattop and RF system would also allow for higher beam currents and improved energy efficiency of the facility [2,3].

Concluding, in 2020 the proton facility will be operated with a maximum current of 2.0 mA utilizing a slanted target as described above. User operation will start on 18 May 2020.

Swiss Light Source

With 99.2% the SLS achieved in 2019 the best beam availability in its entire history. The Mean Time Between Failures, 153 hours, was again excellent, only the Mean Time Between Distortions was rather low with 31 hours.

There were just two outages of more than five hours. An outage of the Personnel Safety System (PSYS) caused an interruption of about five hours. A defective auxiliary power supply turned out to be the cause of the malfunctioning. A defect in an RF station caused an outage of about twelve hours: the Booster klystron amplifier had to be used to extract a spare part; this was possible since the Solid State Amplifier (SSA) replaced it for Booster operation.

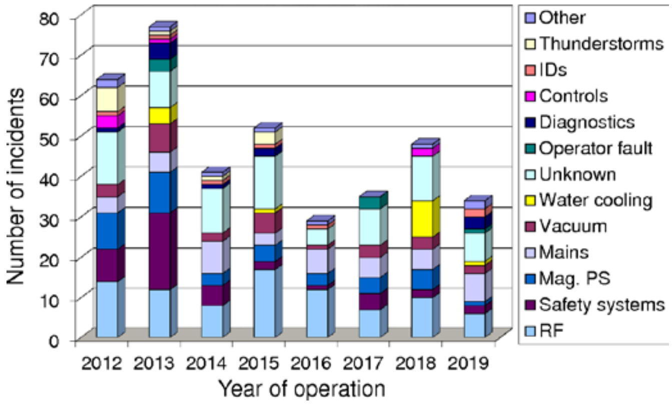

Figure 4: Beam outage count per system for the SLS.

Figure 4 shows which subsystems caused beam outages in the past years. Trips of the mains were more frequent than trips of the RF in 2019. The number of beam trips for unknown reasons remains at a constant level.

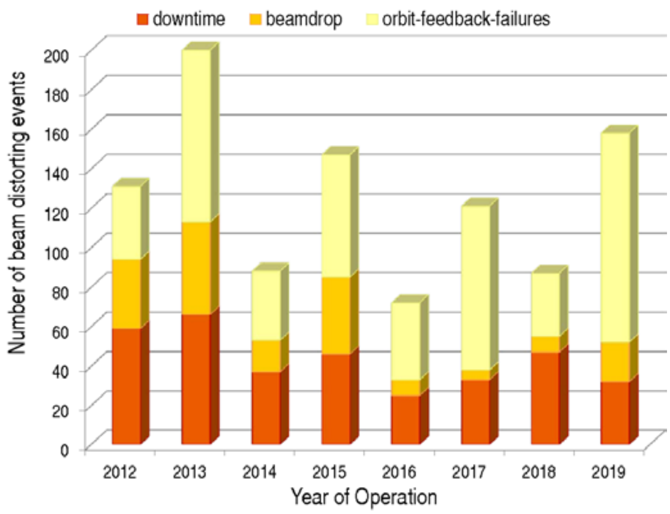

Figure 5: Number of beam distortions at the SLS.

Figure 5 shows the count for different beam distortions in the past years. The number of orbit feedback failures increased again, to about the average for odd years. The type of failure sources expanded: in addition to faulty readings from electronics, we suffered from bad cables and aging connectors. A full prototype for a new BPM electronics will be ready for testing in the second half of 2020; we plan to commission a mini-series of the new electronics in the SLS storage ring, before the long shutdown to build SLS-2.0 in 2023. This will help to fix all teething troubles of the new electronics and allow for a swift commissioning of the full system in 2024, during the start-up of SLS 2.0.

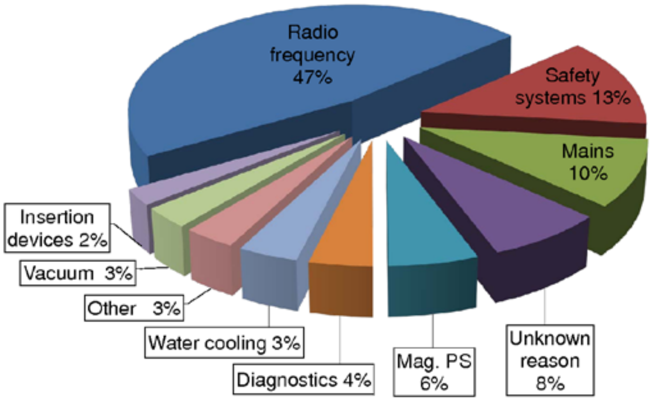

Figure 6: Beam outages per failure category for the SLS.

Figure 6 shows the percentage of the beam outages attributed to the different failure categories. The largest fraction of downtime was caused by the RF – two third of this was contributed by the single twelve hour incident. The second highest percentage was from the safety system; here the single five hour event was the dominating factor.

Table 2 shows the operation statistics of the past two years.

Table 1: Operational statistics of the Swiss Light Source

Beam Time Statistics for SLS	**2019**		**2018**	
Total beam time	6736 h	76.9%	6824 h	77.9%
• user operation	5056 h	57.7%	5144 h	58.7%
- incl. compensation time	160 h	1.8%	160 h	1.8%
• beamline commissioning	860 h	9.7%	840 h	9.6%
• setup + beam development	920 h	10.5%	840 h	9.6%
Shutdown	2024 h	23.1%	1936 h	22.1%
User operation downtimes	32		44	
• unscheduled outage duration	42 h	0.8%	49 h	0.9%
• injector outage (non top-up)	6 h	0.1%	3 h	0.1%
Total beam integral	2512 Ah		2560 Ah	
Availability	99.2%		99.1%	
Availability after Compensation	102.4%		102.2%	
MTBF (mean time between fail.)	153 h		114 h	
MTTR (mean time to recover)	1.3 h		1.1 h	
MTBD (mean time between distortions)	31 h		59 h	

A new filling pattern was tested in 2019 providing a 30% longer beam lifetime [4]. The new filling will be utilized for user operation in 2020.

PROSCAN

In 2019 the cyclotron and beamlines for the proton therapy facility PROSCAN at PSI were again operating with an up-time of more than 7300 hours.

The up-time shown in Fig. 7 reflects the time that cyclotron and beamlines were in the status "ready for beam delivery", relative to the scheduled beam time. 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 98.9%.

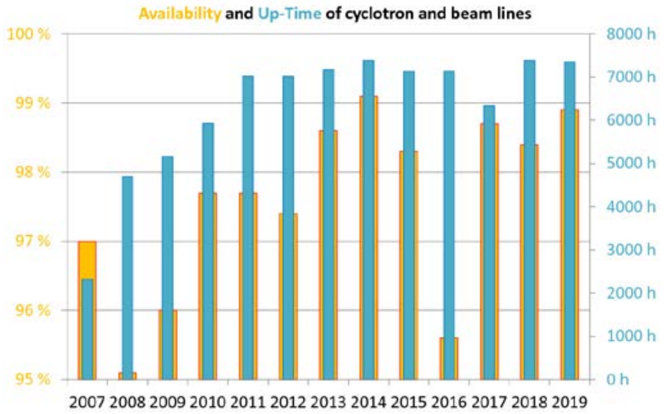

Figure 7: Operating hours per year and availability of PROSCAN

The causes of the unscheduled downtime show a different distribution compared to before (Fig. 8). The RF performed better, but approximately 18 hours have been lost due to problems in the beamlines. These were mostly related to interlocks in Gantry-3, following a small misalignment of the beam at the gantry coupling point. Much effort went into improving the stability of the beamline, but since the beam optics design of Gantry-3 is more sensitive to such deviations than Gantry-2 and OPTIS, such interruptions have increased, now that Gantry-3 is in routine operation. The downtime due to cryogenics was caused by a necessary service of some of

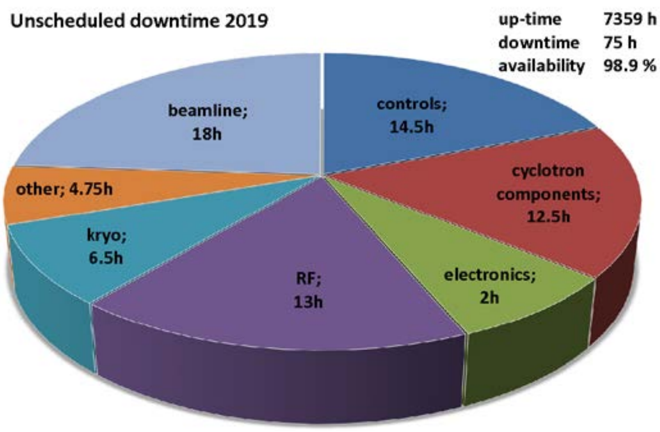

Figure 8: Beam outages per failure category for PROSCAN.

the cryo-coolers. After the warm-up of the SC coil in 2017, all cryo-coolers were replaced and for all of them we were confronted this year with a rather similar time until they needed their services. By exchanging some cryo-coolers a bit earlier than necessary, we expect to spread this risk over a longer time in the future.

Due to a lack of resources and outdated control electronics, we have not been able to repair the system measuring the phase of the beam extracted from COMET. Therefore, this severe operational problem is still present and has resulted in many short beam unavailabilities due to frequently necessary manual retuning of the COMET cyclotron.

As reported before, there is a large asymmetry in the intensity of extracted beam from COMET as a function of the voltage over the vertical deflector plate, which is used for fast intensity control by deflecting the beam out of an aperture in the cyclotron centre. In a symmetric situation, the maximum should be at zero Volt and the curve should be more or less similar for positive and negative deflection voltage. Following the conclusions of the beam optics studies performed in 2018, we have tested the response of the vertical deflector voltage for several ion source chimneys with an extraction hole shifted upwards by 0.6 mm. Figure 9 shows that this indeed helps a lot to achieve a symmetric situation. Further beam studies are planned in 2020.

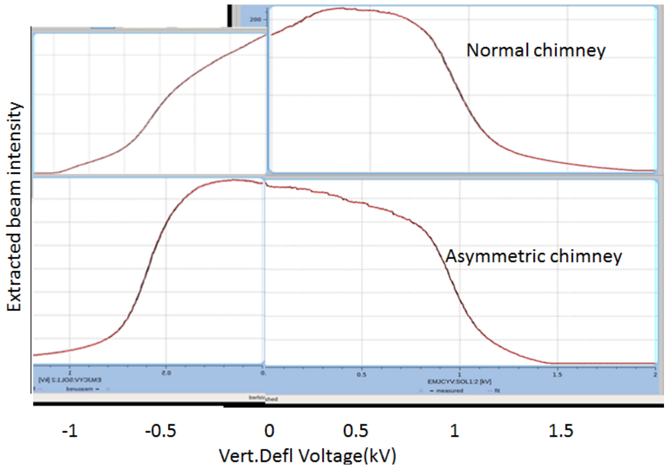

Figure 9: Intensity of extracted beam from COMET as a function of Vd, the voltage at the vertical deflector plate for two different chimney hole positions.

In the beamline of PROSCAN a new non-interceptive beam diagnostics was tested: a beam intensity monitor and a beam position monitor. Both devices worked on a resonating cavity principle, in which the beam position monitor consists of four cavities, as shown in Fig. 10. The 72 MHz structure of the proton beam excites these cavities linearly with beam intensity. After installing both detectors in the beamlines, measurements in realistic beam conditions were performed.

As shown in Fig. 11, the intensity monitor has a low detection limit

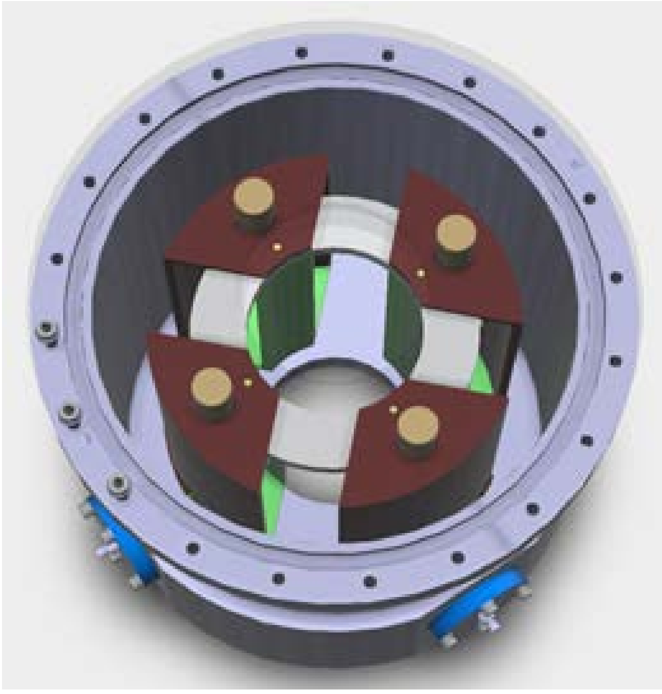

Figure 10: Axial view of the beam position monitor, which consists of four cavities surrounding the beam.

below 0.15 nA. In 2020, the monitors will be implemented in PROSCAN and connected to the control system for routine use.

Intensity monitor.

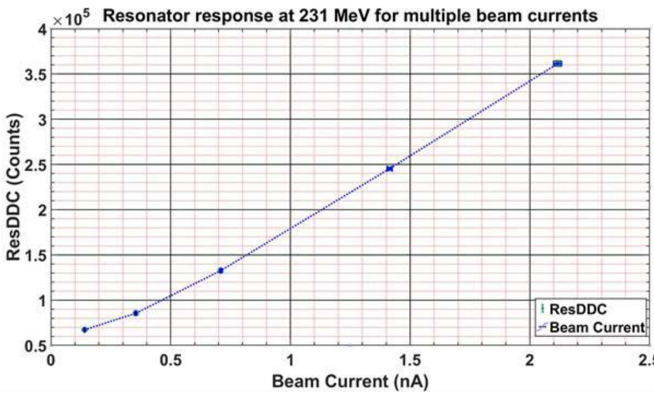

Figure 11: Measured response of the non-interceptive beam Intensity monitor.

First experiments with the beam position monitor have indicated that the monitor can detect the beam position with an accuracy of 0.5 mm.

SwissFEL

2019 marked the first year of regular user operation for SwissFEL, with one beamline, Aramis in full operation. There were two user runs with eight experiments each, in each case five experiments at the Alvra end station and three experiments at the Bernina end station, giving a total of 16 experiments. User run 1 lasted from January to June, user run 2 from July to November. (The month of

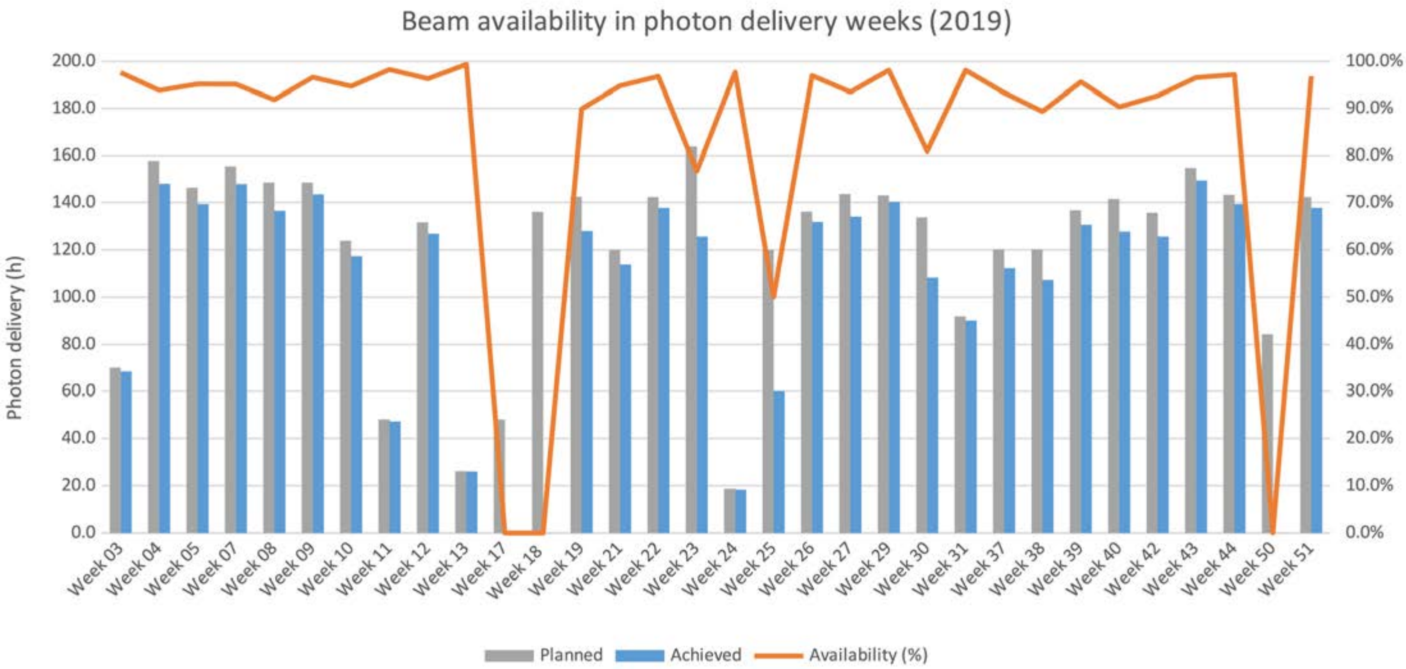

Figure 12: SwissFEL operation statistics during photon delivery weeks in 2019.

December was fully dedicated to the commissioning of the second beamline, called Athos.)

All scheduled user experiments could be performed as planned. 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 12 summarizes the beam availability during weeks dedicated to photon delivery. The availability shows some strong variations, which are typically the result of specific problems (e.g., failure to establish lasing after an undulator re-alignment in week 18, control system glitches in week 25, or waiting for operation clearance by regulatory authority in week 50). The overall availability (not taking into account beam quality) during photon delivery weeks amounted to 85.7% in 2019.

Apart from the end-of-year break, there were three long shutdowns, in April, August and November, allowing access for maintenance, repair and installation work. Between the shutdowns, a maintenance window of 31 hours is scheduled about once per month.

In 2019, SwissFEL finally reached all of its design parameters: in January, the nominal maximum photon energy of 12.4 keV was achieved, exceeded in September by a short run at an energy of 12.5 keV. These photon energies were obtained by pushing the electron energy up to 6.2 GeV. New records could also be set for the energy per photon pulse, which determines the number of photons per pulse, an important requirement for the users. During 2019, photon pulse energies approaching a millijoule could be reached (550 µJ at 12.0 keV, 680 µJ at 9.0 keV, 780 µJ at 7.2 keV, and 900 µJ at 3.7 keV). The duration of the photon pulses, as derived from measurements of the electron bunch length, was typically between 30 and 50 fs (rms), well within the experiments' requirements.

The nominal repetition rate of 100 Hz has been demonstrated repeatedly for the FEL, but not yet for the experiments, where control system and data acquisition issues still prevent operation at more than 50 Hz. Most of the experiments were carried out at this repetition rate, four at a still lower rate of 25 Hz.

Apart from the data acquisition problems, the main issues encountered during the 2019 runs concerned the machine stability and reproducibility. Instabilities in the gun laser at the electron source and in the accelerating RF systems directly translate into beam instability affecting the FEL performance. Such system instabilities were addressed by additional feedback loops and changes in operating points, but further studies and improvements are needed to improve the over-all performance.

The reproducibility of the FEL output power, i.e., the photon pulse energy that can be reached after a shutdown of the facility, suffered in some cases from the large number of changes applied to the systems during the break as well as from inadequate setup procedures during the start-up sequence.

Enhancing the reproducibility of the lasing setup is a focus of current activities and will be crucial for establishing SwissFEL as a reliable user facility.

A large fraction of the machine development shifts was dedicated to establishing FEL operation modes beyond the standard SASE (self-amplified spontaneous emission) mode. Here, both so-called special modes foreseen for the Aramis beamline could be established during the reporting period. In the large-bandwidth mode, the photon spectrum is enlarged by lasing with an electron bunch with an enhanced correlation between energy and longitudinal position along the bunch (energy chirp). The mode was successfully demonstrated for photon energies ranging between 6 and 12 keV with bandwidths exceeding 2% (FWHM) and photon pulse energies of a few hundred microjoules. It was subsequently utilized in a serial protein crystallography experiment at a photon energy of 6 keV.

In the other special mode, the ultra-short pulse mode, the electron bunch is longitudinally compressed to extremely short length, allowing the generation of correspondingly short photon pulses in the attosecond regime. Also this mode was demonstrated in the machine, but still awaits its first application in a user experiment.

On the technical side, machine development work focused on the stability improvements mentioned above and on the introduction of more beam feedback loops. An arrival-time feedback now ensures that the photon pulse reaches the experimental station with an rms jitter of 40 fs, while a pointing feedback keeps the FEL beam position constant at the location of the sample.

Throughout the year installation and commissioning work on the second FEL beamline Athos continued. Several important milestones were reached: the first undulator of the new line was installed in October, the full length of the Athos beamline, with only two of the planned 16 undulators installed, was pumped down in November to allow for beam tests in December. Early in December, the simultaneous operation of both beamlines could be established after the deployment of a new timing system. Soon after, the first electrons reached the Athos beam dump and spontaneous radiation could be observed from the undulators. After two weeks of intense beam commissioning, first lasing in the Athos line, achieved with just two undulators and a delay chicane in between, was observed on 17 December.

The planning for 2020 envisages a slightly reduced number of user experiments to allow for the further consolidation of operational procedures to setup and run the machine. Major project goals for 2020 include first demonstration experiments with FEL beam from the Athos line as well as a first pilot experiment in the third Aramis end station, called Cristallina.

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