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Operation of the PSI Accelerator Facilities in 2023

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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 restrictions due to the 2022 energy crisis were no longer strongly felt during the operation of the High Intensity Proton Accelerator Facility (HIPA) in 2023, but the delay in the procurement of spare or replacement parts due to the difficult global logistics situation still existed and had an impact for both normal and extraordinary maintenance work. The shutdown maintenance work started on time in the second week of January, and in addition to the usual work, some major activities were also planned, such as repairing the electron trap on the linear accelerator (EWF), installing a new tuner for the new Resonator 2 and replacing the defective amplifier with a new SSA for the old Resonator 4, both for the 72 MeV injector 2. For the operation of the secondary beamlines it was also necessary to replace a defective ceramic isolator in Spin Rotator 1, which was malfunctioning during the previous year of operation (2022). In the UCN beamline, one of the harps position monitoring devices also required repair.

On April 13th we got the unpleasant surprise of a water leak in one of the coils of dipole magnet AHD2 in the 590 MeV proton beamline. Thanks to the joint efforts of many colleagues it was possible to replace both coils and proceed with the commissioning of the machine in time for the preparation of user operation, which was brought forward by 9 days compared to the time originally planned, while the shutdown work was already underway. In fact, a communication was received in early March from the European Space Agency (ESA) and Dassault Systems requesting that SINQ begins user operations earlier, on May 2nd instead of May 25th as planned. Due to the volume of foreseeable and unforeseeable work, however, the shutdown could not be shortened by that much, so an agreement was reached to hand over the beam to users on May 16th.

The overall availability of the HIPA facility during the 32 weeks of operation in 2023 was 91.3%, a real setback compared to the 34 weeks of the record year 2022 (94.4%). A closer look at the two years shows, however, that apart from the weeks of major breakdown, the availability during weeks with a rate >90% (96% in 2023 vs. 96.5% in 2022) and the amount of these weeks (26 in 2023 vs. 27 in 2022) are very similar for the two years, confirming the tendency of HIPA operate with good performance.

What made the difference were the few weeks (6 in 2023 vs. 7 in 2022) where availability fell below 90%: for these weeks we recorded an average availability of 66.0% in 2023, compared to 84 .7% in 2022.

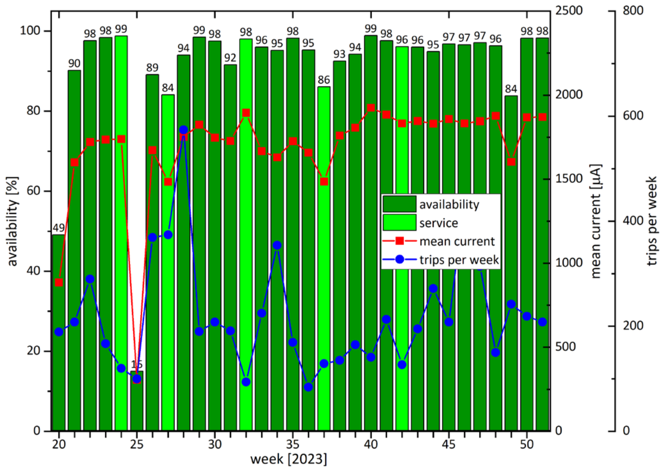

Figure 1: Weekly availability of the High Intensity Proton Accelerator Facility in 2023. Due to a request for beam time by the European Space Agency the beginning of the operation was set to May 16th instead of the originally planned May 25th.

During the first (short) week of operation (week 20/2023), from May 16th to May 18th, there were good and bad news: on the one hand the nominal beam current (with only two resonators in the Injector) of 1800 µA was reached, on the other hand some of the old CAMAC control cards started losing values randomly, causing a serious drop of beam availability (49.1%). As the problem with the control cards seemed to have vanished, HIPA operated with increasing availability in the following weeks, from 90.2% to 98.8%. At the same time Resonator 4 was ready such that a beam current of 2000 µA was envisaged and could be reached within a few weeks.

The electrostatic extraction element EEC started showing abrupt changes in dark current during week 21, an issue that persisted until the end and is most likely associated with an almost periodic plasma formation within the Ring accelerator. Unfortunately, the aforementioned control card issue occurred again, this time causing a massive drop in availability to a dramatic low of 15.0% during week 25/2023.

In week 27, a breakdown of the flattop cavity in the Ring accelerator caused 8.2 h downtime. 4.6 h downtime in week 28 were due to the new solid state amplifier for Resonator 4, and 8.6 h in week 31 to a burnt fibre optic cable at the accelerator tube. Power supply malfunctioning accounted for 6 h in weeks 36 and 37.

Towards the end of the year, in week 49, beam delivery was interrupted for about 20 h by an isolation problem at the high-voltage generator (810 kV) for the linear accelerator. Finally, HIPA greeted the end of the year with over 98% availability during the last two weeks.

The outage statistics (Fig. 2) show that the problems with the control cards accounted for the largest portion with 195 h (61.6%). In Injector 2, we could successfully commission the new Resonator 2, with a beam current of up to 1 mA through the Ring cyclotron. During the shutdown 2024, the last new Resonator 4 will be installed, but its commissioning will only occur during a service period in 2024 (Q3). Thus, operation will start with three resonators, where 2.2 mA should be possible.

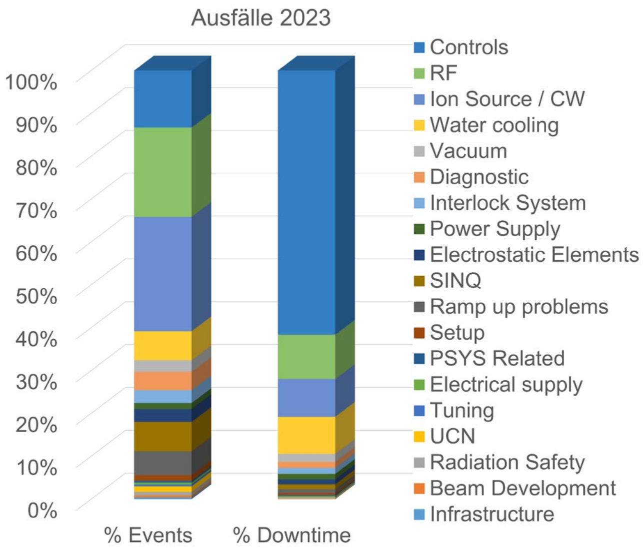

Figure 2: Beam outages per failure category at HIPA. The vast majority of downtime is due to the old control cards.

Table 1: Operational statistics of the High Intensity Proton accelerator Facility for 2023.

Statistics summary	**2023**
Total scheduled user beam time	**4528 h**
Deposited charge: total / during user time	
to meson production targets	8.37 Ah / 6.67 Ah
to SINQ	5.67 Ah / 5.34 Ah
to UCN	0.08 Ah
to isotope production targets	0.008 Ah
Outages (current < 1 mA)	
long outages (t > 5 min):number / total time	233 / 316.6 h
total number / total time	6288 / 392.1 h
Average beam current to meson targets	**1693 μA**
Availability	**91.34%**

Swiss Light Source

The Swiss Light Source (SLS) operational year 2023 proceeded as scheduled with the final cease of operation after the ceremonial beam dump during the early morning of Saturday, the 30th of September. Since then the accelerator tunnel roof has been removed making way for the dismantling of the SLS storage ring followed by the sector-wise installation of the new SLS 2.0 storage ring. Even though the beam availability of 92.3% achieved in 2023 was the worst in the entire operational history of the SLS, it still remains comparable to other synchrotron light source facilities. With four days the Mean Time Between Failures stayed good despite many ongoing preparations for the SLS 2.0 project. The Mean Time Between Distortions, like beam outages, interruption in top-up or beam orbit distortions, remained at 18.6 hours.

Despite the by 30% reduced user operation time in 2023, the number of downtime events during user operation was unfortunately still well in line with the average of recent years. Some longer outages were also encountered: The longest outage causing 73% of all user operation downtime was caused by a water-to-ultrahigh-vacuum (UHV) leak at an absorber. During this event the vacuum of the entire arc number 12 went up to 20 mbar. Luckily over half of the overall required 17 days to get back to normal user operation conditions fell into scheduled shutdown time reducing the impact on the beam availability to just over a week. Two further outages exceeded five hours: A water leak in the LINAC at a coil of one of the ten QT-type quadrupoles manufactured in 1991 and previously installed at the Amsterdam Pulse Stretcher caused 17 hours of user operation downtime. In recent years, several of these quadrupoles have had water leaks. A further 17 hours of user operation time were lost due to a bearing damage on the compressor screws of the cryoplant for the superconducting third-harmonic cavity.

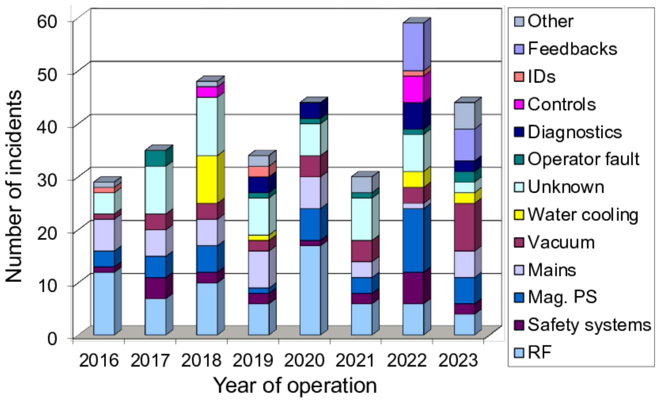

Figure 3: Beam outage count per system for the SLS

Figure 3 shows which subsystems caused beam outages in the past years. In total 44 outages during the 3504 hours of user operation in 2023 were recorded. Whilst 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, the most severe interruptions of user operation can be attributed to the ageing machine, i.e., leaks and other apparent effects of wear and tear.

Figure 4 shows the count for different beam distortions in the past years. The last five years have shown a slightly increased number of orbit feedback outages. Many of these outages are related to the very old BPM electronic hardware.

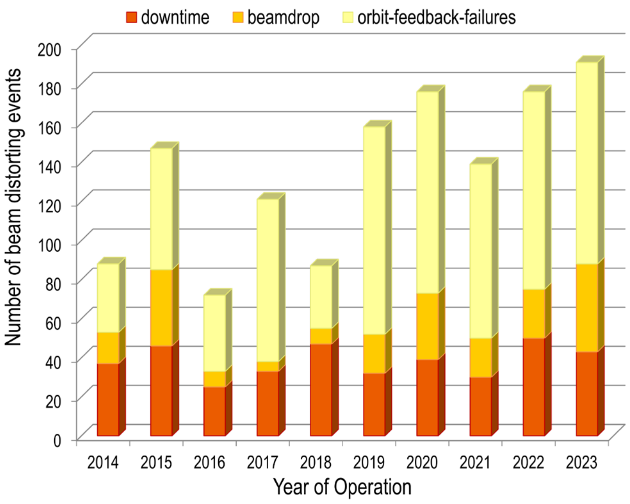

Figure 4: Number of beam distortions at the SLS

Prototypes of the new system have been successfully tested at the SLS during the last week of operation. This week was dedicated to machine development studies in preparation for the SLS 2.0 upgrade, which will include an entirely new BPM and orbit feedback system.

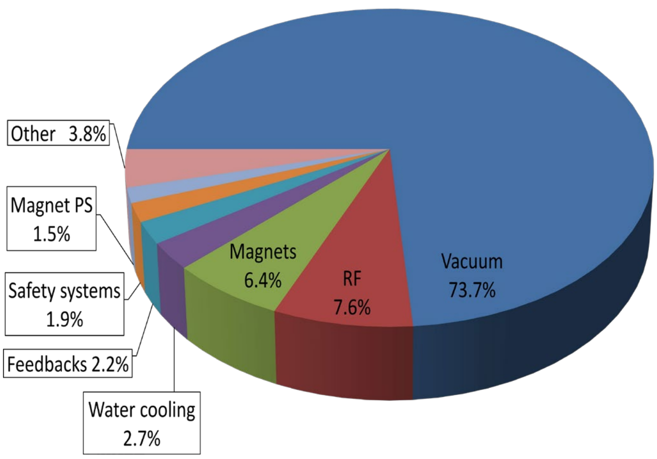

Figure 5: Beam outages per failure category at the SLS

Figure 5 shows the relative contributions of the different systems to the total downtime. The aforementioned water-to-UHV leak caused most of the downtime. The failure rate of all the other systems remained within the usual range. The operational statistics of the SLS in 2023 are summarized in Table 2.

Table 2: Operational statistics of the Swiss Light Source

Beam Time Statistics for SLS	2022		2023	
Total beam time	6512 h	74.3%	4872 h	55.6%
• user operation	4960 h	56.6%	3504 h	40.0%
- incl. compensation time	96 h	1.1%	72 h	0.8%
• beamline commissioning	744 h	8.5%	448 h	5.1%
• set-up + beam development	680 h	7.6%	920 h	10.5%
Shutdown	2248 h	25.7%	3888 h	44.4%
User operation downtimes	50		36	
• unscheduled outage duration	128 h	2.6%	271 h	8.0%
• injector outage (non top-up)	13 h	0.2%	10.8 h	0.3%
Total beam integral	2373 Ah		1570 Ah	
Availability	97.4%		92.3%	
Availability after Compensation	99.3%		94.7%	
MTBF (mean time between fail.)	97.3 h		91.6 h	
MTTR (mean time to recover)	2.6 h		7.5 h	
MTBD (mean t. b. distortions)	27.3 h		18.6 h	

PROSCAN

In 2023 the cyclotron COMET and its beamlines for the proton therapy facility PROSCAN at PSI were in operation with an uptime of 7545 hours. This was the highest uptime since 2007, the start of the patient treatment with COMET, breaking the record from last year. The uptime includes scheduled patient treatment between Christmas and New Year as every year. There were only eight days scheduled with no beam, one of which was caused by the PSI (West) site-wide system test of the electrical power. The uptime in Fig. 6 reflects the time that cyclotron and beamlines were in the state “ready for beam delivery”, during periods scheduled for beam.

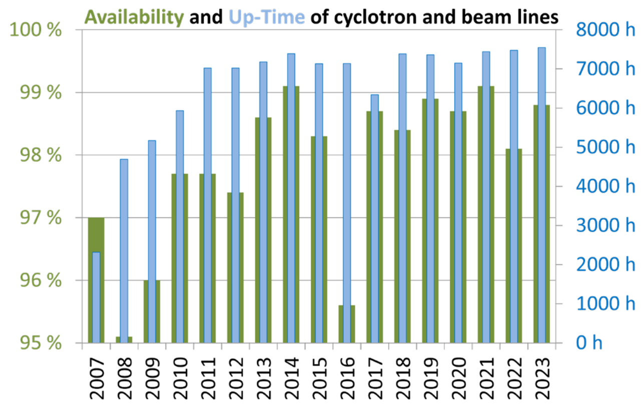

Figure 6: Operating hours per year and availability of PROSCAN. Downtime due to interlocks from the patient treatment side is not included in these statistics. With an availability of 98.8%, 2023 is one of COMET’s top performance years. For 33 weeks, i.e., more than half the time of the year, there was no failure at all. This good performance is only possible through maintenance work on weekends and evenings and through the rapid intervention of on-call expert teams in the event of a failure.

The causes of the unscheduled downtime of 95 h are shown in Fig. 7. Three quarters of the outages are caused by RF systems and power supply failures. More than half of the RF downtime, 28 h, is due to the exchange of the RF window, which separates the RF feed-through in vacuum from air. It had already been in operation for 6 years and was scheduled to be replaced by a newer one. The exchange and commissioning were successful, but later rising temperatures and several RF failures ultimately made it necessary to reinstall the previous RF window. Although the RF experts worked on Sunday, the loss of one patient treatment day was unavoidable. Several events caused the downtime due to power supply failures; some were connected to the kicker magnet. The longest outage lasted 9 h. The power supply driving the superconducting coils for the main magnetic field in the cyclotron was successfully replaced by a newly purchased spare part in a maintenance weekend, not due to a failure but to verify its flawless operation. The automatic discharging of the current in the superconducting magnet was involuntarily tested when a sudden pressure drop in the water cooling circuit switched off the power supply during RF trouble shooting.

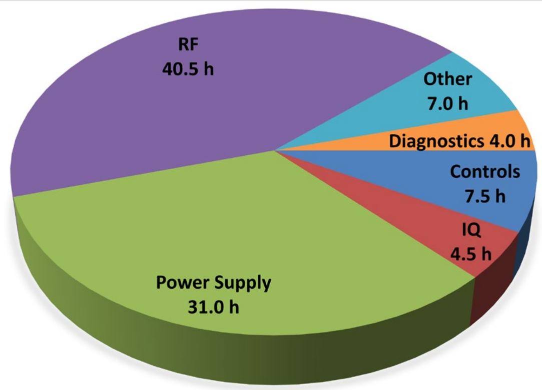

Figure 7: Unscheduled downtime for 2023 by causes.

It is particularly pleasing that the outages of the ion source could be reduced significantly, from 55 h in 2022 to 4.5 h. Only one unscheduled source service was necessary. In the first half of the year still several rapid shutdowns of the ion source were triggered by a defective module, which was exchanged end of June. In August a new ion source was installed to test the spare part. Instabilities could be resolved by carefully choosing the operation settings. However, the set-up of COMET remained difficult until the cathode was exchanged in late October. Since then, it is working reliably. Another great result is that downtime due to failures in the control system could be significantly reduced from 57 h in 2022 to 7.5 h.

In Table 3 the key performance data 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	**2023**
Scheduled beam time	7640 h
Beam current integral	224 µAh
Up-Time	7545 h
Outages	95 h
Availability	98.8 %

In the beginning of the year a few high voltage arcs were observed on the vertical deflector plate in one of the four Dee noses in the cyclotron. As a precautionary measure the noses (top & bottom) and the associated deflector plates were then successfully exchanged during a service weekend.

On the 17th of June, after several test installations, the degrader made of boron carbide was finally installed and went into clinical operation the following day after extensive acceptance tests performed by the experts of the Center of Proton Therapy (CPT). The purpose of the degrader is to reduce the energy of 250 MeV delivered by COMET to the energy needed for the proton therapy in a fast manner (80–100 ms, the fastest energy modulation in the world). For example for the treatment of eye melanomas with OPTIS 2, 70 MeV are needed. When the proton beam passes through matter, its intensity drops to a fraction of a percent at 70 MeV due to scattering. Using boron carbide instead of graphite, the material used in the previous degrader, increases the proton transmission by more than 30%, due to its higher material density combined with a lower proton density. The effective irradiation times at OPTIS 2 were hence reduced by more than 30% (Fig. 8).

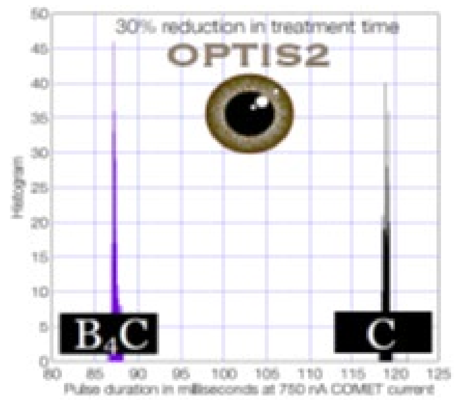

Figure 8: The duration of the 340 pulses for treatment at OPTIS 2 is 30% shorter with the B4C degrader compared to a graphite degrader (C). Courtesy of CPT.

Several methods to further increase the transmission of the proton beam in the energy selection system for enabling ultrafast treatment delivery within a breath-hold of the patient were studied in a PhD thesis [1]. A polyethylene wedge that is inserted into the dispersion area instead of the momentum-restricting slit is promising. It reduces the momentum spread by slowing down the particles with higher momenta at the cost of increasing emittance. A test in the beamline of OPTIS 2 increases the transmission by a factor of two keeping the same momentum spread as without wedge [2].

For the non-destructive low-beam-current monitor (BCM), which was recently developed as part of a collaboration between Bergoz Instrumentation, PSI and Instrumentation Technologies, two beam tests were performed with the aim to measure the linearity of the device over a wide range of currents. One of the cavities was tuned to the second harmonic resonance, the other to the third harmonic of the COMET beam pulse repetition frequency (72.85 MHz). As reference for the measurement an ionization chamber and a Faraday cup were used. For the measurements, beam currents were varied between 1 nA and 750 nA, the higher currents being interesting for FLASH therapy while the low currents are applied in conventional proton therapy. The BCM behaved perfectly linear at the second harmonic compared to the Faraday cup, whereas the ionization chamber, as expected, showed non-linearities. More information can be found in [3].

In the second half of September large losses occurred at the phase slits built into the cyclotron close to the ion source to remove spurious beam. An extra tuning shift was necessary to increase the extraction efficiency of the beam out of the cyclotron. In addition, puller and bridge (including the fixed slit) close to the ion source were replaced the following weekend.

No serious power outages affected the operation and patient treatment in 2023, but several very short power drops switched off the ion source and the RF supply. A diesel emergency power station is in preparation to prevent long shutdowns due to the warm-up of the superconducting main coils.

SwissFEL

Seven years after the first electron beam, SwissFEL is now firmly established as a user facility. The performance in terms of peak power, beam availability and delivered beam time reached new records in 2023. Major installations in the machine are slowly coming to an end. The Athos tuning C-band linac and the X-band deflecting cavity (developed in collaboration with DESY and CERN), both installed in 2022, reached nominal performance in the beginning of 2023 and are now in routine operation. The HERO/EEHG installation was completed in the beginning of 2023 with the installation and commissioning of the EEHG modulator and chicane. The HERO seed laser scheme, to produce trains of attosecond pulses, was demonstrated and is now operational. The EEHG part of the scheme which is aiming at producing X-ray pulses with a high spectral brightness, phase-synchronized with an external source, is under development. More results are expected in 2024.

Five end-stations – Alvra, Bernina and Cristallina on the Aramis branch and Maloja and Furka on the Athos branch – are now in operation and taking beam routinely. There were in total 18 user runs at Aramis and 8 at Athos in 2023. Cristallina saw its first pilot runs in spring and started in-house user operation in September. Cristallina will start full user operation in 2024 after a first call for proposals in 2023. Furka also had its first pilot-runs in 2023 and will start user operation in 2024.

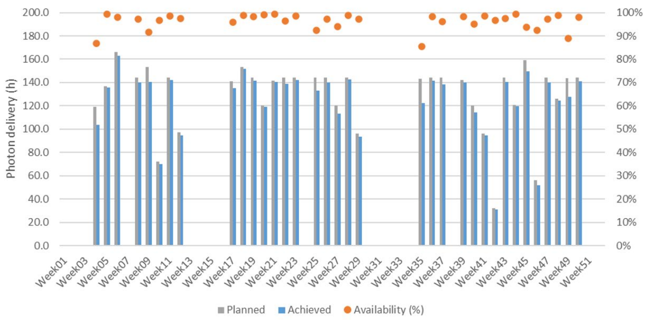

Figure 9: SwissFEL Aramis operation statistics during photon delivery weeks in 2023.

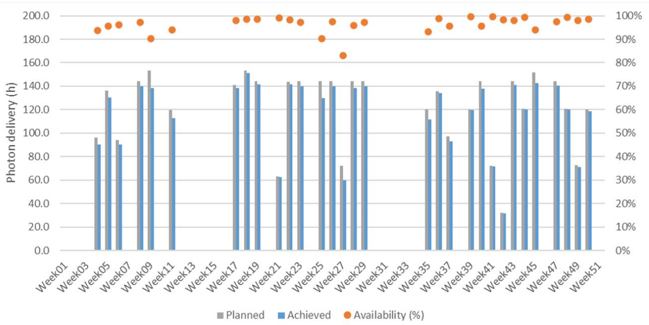

Figure 10: SwissFEL Athos operation statistics during photon delivery weeks in 2023.

The beam-time share increased again in 2023. Aramis delivered a total of 4529 h (+1.3%) of photon beam operation and Athos 3779 h (+5.9%). This represents, respectively, 51.7% and 43.1% of the year. These are very high values for a FEL machine, given that each end-station receiving beam requires a dedicated set-up, and in many cases beam parameters are changed several times during a run. Last year saw no major technical incident and the availability of subsystems, in particular RF, was very good. Consequently, the beam availability reached new records, with an overall beam time availability of 96.2% for Aramis (94.5% in 2022) and 96.3% for Athos (92.2% in 2022). These good performances, and their constant improvement in the last years, reflect the progress made in the operation and maintenance of the machine, and the high level of support of the technical teams. There were nevertheless a few minor incidents, most of them related to controls issues (motor controls, inappropriate handling of alarms) or human errors (inaccurate diagnostics of problems leading to longer downtimes, missing reset after a system maintenance). Such problems are in principle easily curable, through system consolidation and training, which should lead to further improvement in reliability. Outside these few incidents, the beam availability remained very good, often close to 99%. Figures 9 and 10 summarize the beam availability during weeks dedicated to photon delivery (user operation and beamline development) for Aramis and Athos.

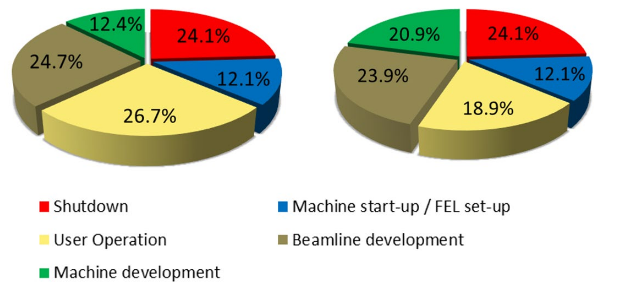

Figure 11: Shift distribution in Aramis and Athos in 2023.

Outside photon delivery, the rest of the year was shared between shutdowns (24.1%), machine development (12.4% for Aramis, 20.9% for Athos) and set-up (12.1%). The share of machine development remains larger for Athos, where special operation modes – especially for seeding operation – still need to be developed and tested. The shift distribution is shown in Fig. 11 and its evolution since the start of the machine is shown in Fig. 12.

Since the energy crisis at the end of 2022, we keep a close eye on energy consumption. Energy saving measures were put in place in 2023, such as, for example, the reduction of the repetition rate in machine development weeks or the reduction of the Linac-3 RF power when the full beam energy is not required for operation. Such measures can reduce the power consumption by up to 30%. In total 700 MWh could be saved in 2023. A further 600 MWh were conserved by extending the winter and spring shutdowns by one week each.

With the increasing number of active end stations and the larger parameter space available (photon energy, pulse length, bandwidth, polarisation, two-color mode, low-charge mode or special compression schemes) the set-up shifts are becoming more challenging. Fortunately, thanks to progress in the operation automation, improved tools and diagnostics, and the gain in operational experience, beam set-ups are becoming faster. The machine settings prepared on Mondays can be restored later in the week with a good level of reproducibility. Automated procedures allow the control room to change the electron beam energy or the Athos undulator polarisation quickly and reliably.

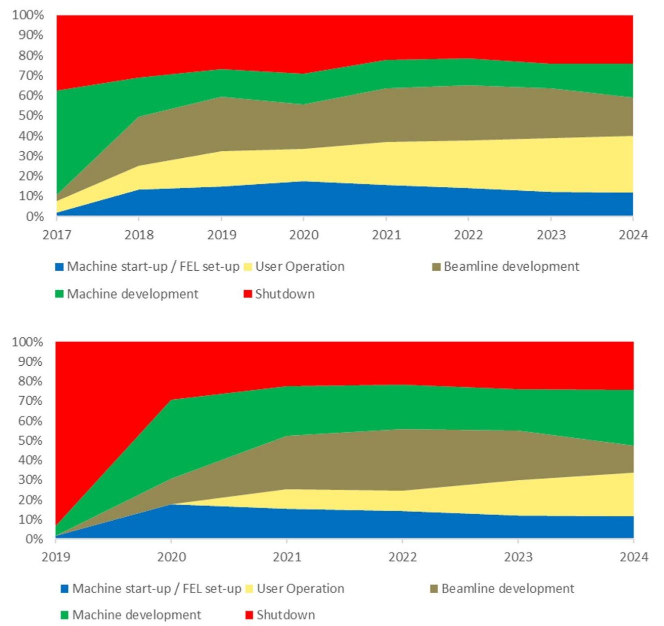

Figure 12: Evolution of the shift distribution for Aramis (top graph) and Athos (bottom graph) 2017–2024.

Although fewer records were broken on Aramis in 2023 – except at the high energy end, where a record 0.9 mJ at 12.5 keV was achieved – the performances remained very high and close to the theoretical limits of the machine. In the Athos branch, on the other hand, new records were achieved for most of the photon energy range with, for the first time, pulse energies above 5 mJ at 530 eV. A selection of beam performance records for Athos is shown in Fig. 13.

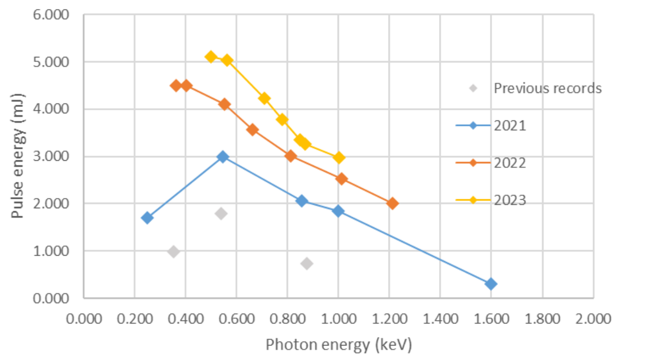

Figure 13: Evolution of the peak performances for Athos in the last three years.

With five end stations in regular user operation and an increasing demand for advanced modes, special set-ups and high performances, 2024 is likely to be a challenging year. Certainly, the machine operation and scheduling will increase in complexity. 2024 should also see further progress with the development of Athos special modes and, in particular, seeded operation.

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