Operation of the PSI Accelerator Facilities in 2017

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The Department of Large Research Facilities has responsibility for the operation and development of the three 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)

Despite a couple of challenges 2017 was again quite successful for HIPA operation. The overall availability of the facility amounted to 93.1%. According to BAG provisions the SINQ target-12 was limited to operate to 5 Ah, later 5.4 Ah total charge, a current density < 30 μA/cm^2 and 29000 thermal cycles.

User operation in 2017 started as scheduled on May 8th (W19) with a production current of 1900 μA extracted from the Ring cyclotron. The facility was ready for operation from the first week of May with 1100-1400 μA on the beam dump. During the first week of operation the number of trips was 554 per week, slightly higher than usual. Figure 1 shows the distribution of the weekly availability over the year 2017, the weekly rate of the beam trips and the averaged beam current onto the meson production target E as well as services with machine development intervals.

The new thick target E (6 cm instead of 4 cm) was taken into operation to provide a reduced current density for SINQ, while extracting higher current from the Ring cyclotron for a reasonably high meson production rate at the secondary beam lines. For the new target the beam optics between target E and SINQ had to be adjusted. In W22 (a service week) the Ring radial phase probe RRI2 was stuck in a certain position and was taken out of operation until the next shutdown. In W29 control modules in collimators KWI21-28 failed and water monitors had to be exchanged because of cooling problems. Until W32 the facility was running smoothly at 91-98% weekly availability and with an UCN was taken into operation. It was agreed that ordinary machine developments should be switched to the beam dump in order to conserve more SINQ operational beam time in terms of total charge and trips. It was estimated that the SINQ target should reach 5 Ah according to BAG requirements given above by November the 8th. W31 began with a power cut on Saturday, which led to 12.5 hours of interruption as a result of difficulties to switch on the CI4 resonator of the Injector 2 cyclotron again. It was decided that during interruptions longer than 30 minutes motors of the two meson targets should be switched off to avoid damage of the bearings.

During the weeks 32-42 the facility was running smoothly again at 93-98% weekly availability with SINQ and UCN in stable operation. During W34 software, hardware and dynamic limits of loss monitors and aperture monitors in the p-channel and in the SINQ beam line have been readjusted. Some limits, such as the MHI11-16, were too high (historically), others, like the MHB5 / MHB6, were too low for operation with a 6 cm target. A water leak in the p-channel at QHC1 took away 6.5 hours of user operation. In W36 the definition of the availability for HIPA was consolidated and defined as beam time with a beam current I > 1 mA extracted from the Ring cyclotron (at MHC1) over the scheduled beam time. This way, the availability also includes UCN kicks, which would not be included when taking the current monitor MHC4. In September, during the service week (W38) the 6 cm target E

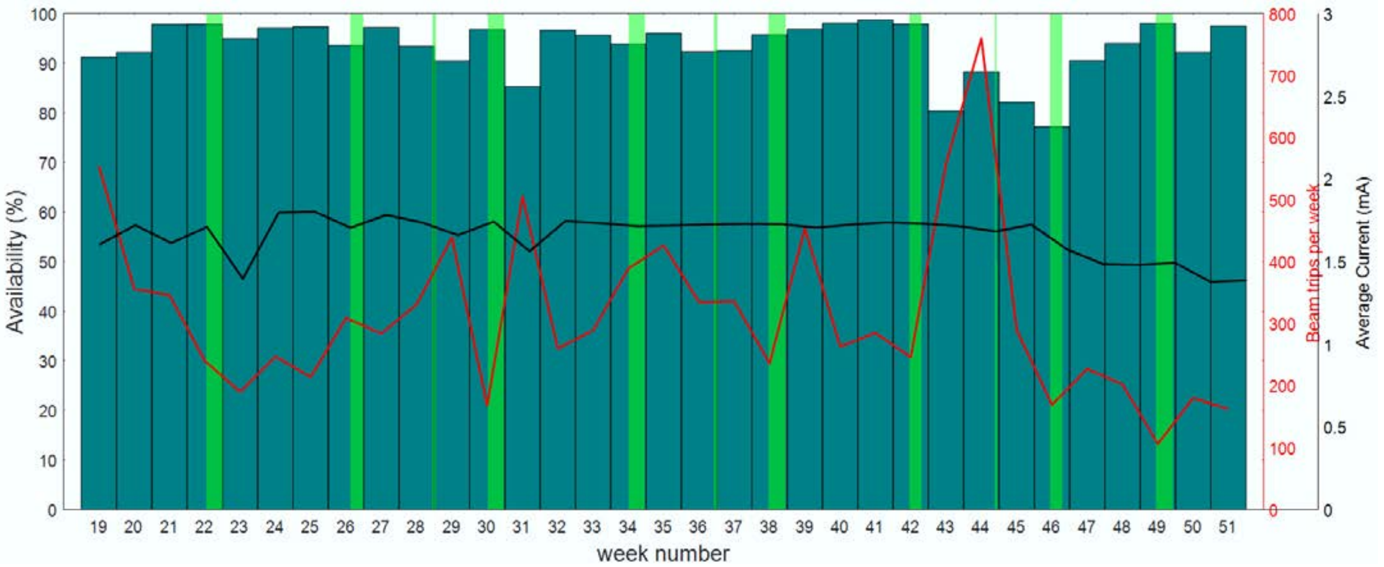

Figure 1: Operation of the Proton Facility (HIPA): availability (jade grey), beam trips (red), average beam current at the target E (black) and services with machine developments (light green).

new type used for the first time. In W41 it was decided to shorten two service weeks in October and November (W42 and W46) by one day of machine development on Thursdays. The extension of SINQ operation until December the 4th was requested to BAG.

W43 had a drop of availability to about 80% mostly due to a damaged electrostatic extraction channel EEC and its exchange (26.9 hours interruption); the trip rate increased significantly due to that (See Fig. 1). Also W43 had operation interruptions due to water cooling interlocks by collimators KX18-19. In W44 the amplifier of resonator CI4 broke down (7 hours interruption) and the operation of Injector 2 was set up with only three resonators with slightly higher extraction losses. In between weeks 44 and 45 a water leak at ASL31 magnet in the experimental area πM3 occurred, which lead to total 18.3 hours of operation interruption and contributed to the lower availability (Fig. 1). In the same week BAG approved the SINQ operation until December the 4th with an accumulated charge of up to 5.4 Ah.

On W46 a sudden increase of the dark-current was detected followed by an EEC break down and an interruption of 8.5 hours. High beam losses at the ANWIKO collimator (Ring injection) were caused by the field fluctuations at the AXE dipole magnet. The centring of the beam was adjusted using the RRI probe, which solved the problem. Also the dark-current interlock limit had to be raised. By W46 problems with target E increased: the motor steering had to be frequently reset and reversed. During the service week 46 target E was exchanged with a 4 cm thick segmented target. Due to the available service time caused by the target exchange, it was decided to exchange the ion source too. The machine's set up after the target and ion source exchanges ran with a delay of 8.3 hours. These two events resulted in the lowered availability of about 77%. The week after (W47) revealed problems with the ion source: EVEX-discharges considerably increased. After one of such discharges the ion source had a problem and was not operable any longer, nominal settings of collimators KV1A/B and beam stopper BV4 were lost and had to be set again after the reboot. From W47 until the end of operation in W51 the machine was running relatively smooth with availability above 90%. On Monday, December the 4th (W49) at 9 o'clock, the SINQ operation was stopped for 2017. On the same week during the service the collimator KHNY21 was removed from the p-channel and put into the parking slot. The rest of the HIPA operation was continued without the collimator. The reason for this action was the still existing leak in the 590 MeV beam dump region. W48 and W50 had 4.9 and 6.8 hours user operation interruptions, respectively, because of PSYS problems in Injector 2 and experimental areas in the p-channel.

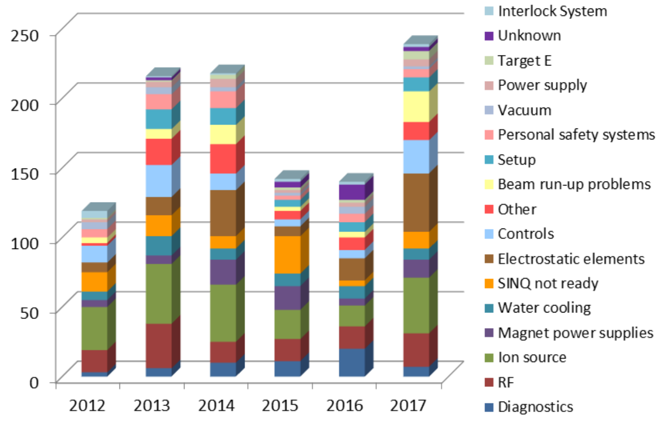

Figure 2: Beam outages count per failure category at HIPA.

Ion source reboots stayed an issue until the end of operation on December 22nd, which can be seen in Fig. 2, mostly contributed by the electrostatic elements (brown) and the ion source (green). The operational data for 2017 for the facility are shown in Table 1.

Table 1: HIPA Operation Statistics

Beam-time statistics for HIPA	**2017**
Total scheduled user beam time	**4838 h**
Beam current integral	
- to meson production targets	7.97 Ah
- to SINQ	4.10 Ah
- to UCN	0.064 Ah
- to isotope production targets	0.013 Ah
Outages: current < 1 mA, time > 5 min	228 h
Availability	93.1 %

The various relative contributions to the downtimes in 2017 are shown in Fig. 3. Major contributions came from electrostatic elements (19.7%), water cooling (20.3%), RF (14.4%), and controls (10.3%).

The old analogue electronics of the beam phase probes (MIFs) in Injector 2 were successfully replaced with digital electronics like in the case of the MRFs in the Ring cyclotron in 2016. For the shutdown the replacement of the old 150 MHz resonator 2 in Injector 2 with a new 50 MHz one is planned. In 2018 Injector 2

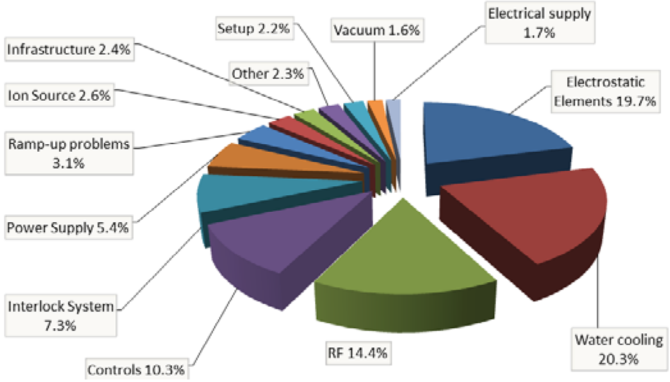

Figure 3: Downtime characterized by category of HIPA outages longer then 5 minutes (ca. 228 hours).

will be operated with only three resonators, which limits the maximum beam current to about 2 mA. In 2019 resonator 2 will then be driven by a new amplifier chain whereupon resonator 4 will be replaced during the shutdown in the same year. Therefore, Injector 2 will be operated with only three resonators also in 2019. Amplifiers for all four resonators are planned to be in operation by 2020.

PROSCAN

In 2017 the cyclotron and beam lines for the proton therapy facility PROSCAN at PSI have been operating with an up-time of more than 6300 hours, which is approximately 800 hours less than normal. This was due to a planned shutdown of the cyclotron in May and June 2017. In this period the insulation vacuum of the cryogenic system of the cyclotron has been serviced to prevent an unexpected cryogenic problem, such as we had in October 2016. During the remaining period of scheduled operation the availability was very high again: 98.7%. As can be seen in Fig. 4, approximately 34% of the unscheduled down time was due to RF problems which occurred both in the amplifier and in the cavity. The other causes show a similar distribution as before. There were no other components that have contributed exceptionally to the unscheduled down time.

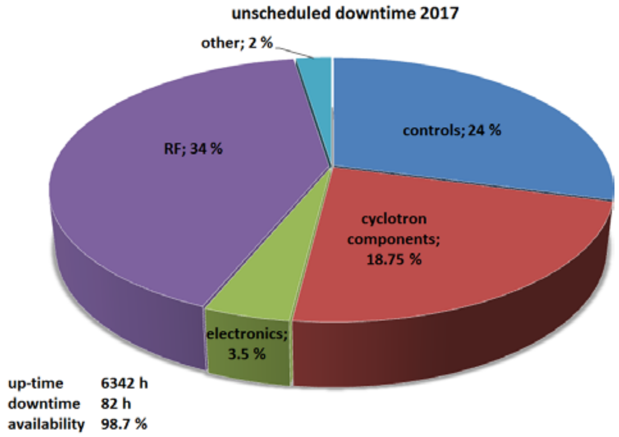

Figure 4: Unscheduled downtime of PROSCAN by causes.

Figure 5 of up-time 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 problem in the cryogenic part in 2016 was probably due to some melting of frozen air in the insulation vacuum. This air has originated from leaking into the insulation vacuum during the more than ten years since the cyclotron has been delivered at PSI. In order to remove this frozen air, we had to heat up the cold mass and insulation vacuum to room temperature, so that the air could be pumped out. In this way the insulation vacuum has been cleaned and it is assumed to be back in the condition we had, when the cyclotron was commissioned at PSI.

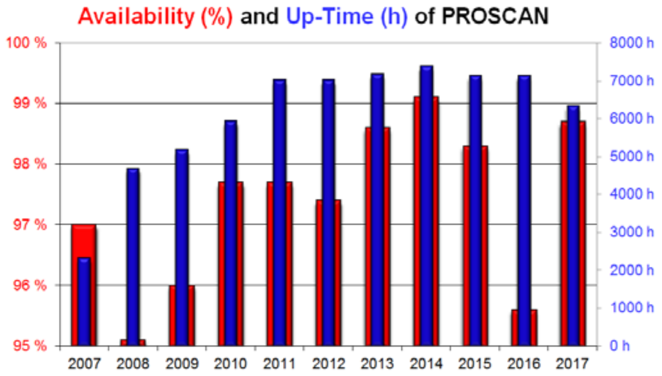

Figure 5: Operating hours per year, availability of PROSCAN.

In the process of heating the cold mass, the temperature increase was not allowed to be too fast, to prevent local variations in the thermal expansion of the coil. After cooling down again, such variations could cause a quench due to mechanical stresses. Therefore we took care that coil temperatures did not differ more than 10 K during the heat-up process. Also much care has been taken to prevent condensation of ambient moisture at the outer wall of the insulation vacuum cryostat. This was to prevent that the condensed water would cause an uncontrolled spreading of the radioactive contamination that has accumulated at the outside of the vacuum tank during the 10 years of operation. Therefore the usual method to heat up the coil by venting the insulation vacuum, has been replaced by a method in which we have used local heating systems of the cryostat, special heat insulation and a forced gas flow to heat the coil only via the volume normally filled with liquid helium. A forced flow of helium gas at room temperature was used until a coil temperature of 100 K was reached after four days. From then on nitrogen gas was used and 300 K was reached after another nine days. The procedures we have pursued during the heat-up process have successfully prevented any condensation of ambient moisture at the outer wall of the cryostat, so no spreading of radioactive contamination has occurred. After the heat-up process a period of two weeks was used to perform repairs and to clean the insulation vacuum using extra pump capacity.

The cooling down process was performed according the normal procedures and took a week. The slow ramp up of the magnet current went smoothly and without a quench. Since no significant differences in beam properties have been observed during the beam development phase, beam was handed over for therapy exactly two months after the start of the shutdown. Since then the cyclotron has worked again with an availability of 98-99%.

Since a typical treatment at Gantry-1 or Gantry-2 usually takes 6-8 consecutive weeks, several additional weeks are needed to ramp down and ramp up the number of patients before and after the shutdown. Therefore the effect on the number of patients was larger than just the shutdown time of two months. So due to the shutdown approximately 25% fewer patients have been treated at the gantries in 2017 and approximately 12% less at the eye treatment facility OPTIS2.

Swiss Light Source

The last year was again very successful for the operation of the Swiss Light Source. While the beam availability of 98.7% was only slightly above the average of the past five years, the Mean Time Between Failures (MTBF) of about one week was the second best in the history of the SLS.

A single event caused half of the downtime in 2017: a water leak at the photon absorber of the X02DA TOMCAT beamline. The leak was at an inaccessible location, the only repair option was to remove the absorber. The first idea was to block the absorber open without water cooling until the next shutdown: since the leak was found during a machine development shift that would have prevented any downtime. But this would have required changes to the machine protection system and would have put the beamline out of operation for five weeks. Therefore it was decided to swap the absorber with the second branch of the same beamline: that absorber is only used to block a very short branch in the tunnel with an X-ray position monitor. Unfortunately the second absorber developed the very same water leak than the first one, as soon as it was reconnected; eventually we had to revisit our first option, to allow beam operation again. In total about 30 hours of user operation were lost due to this event.

The only other outage longer than five hours in 2017 was a broken magnet power supply. The control system reported a broken link to that power supply, therefore the operator called the controls person on call. He searched for about one hour for a controls problem just to figure out that the power supply rack had a broken fuse and therefore the control system could not connect. The magnet power supply had a broken rectifier that caused a short cut in the rack. The power supply expert needed several hours to find and fix that problem. In total the outage lasted for six and a half hours. It appears that the excellent low failure rate of our magnet power supplies start to affect the training level of our experts.

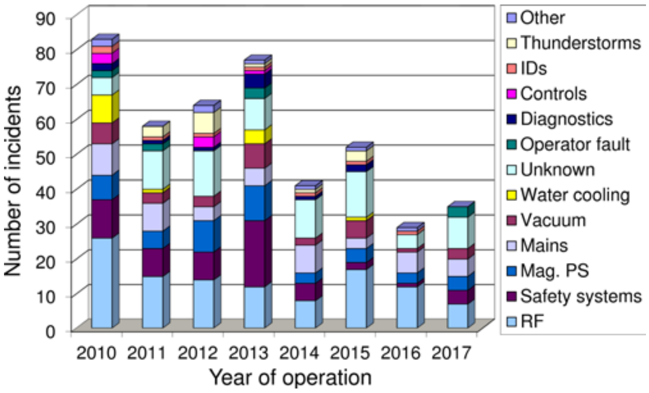

Figure 6: Beam outage count per failure category at SLS.

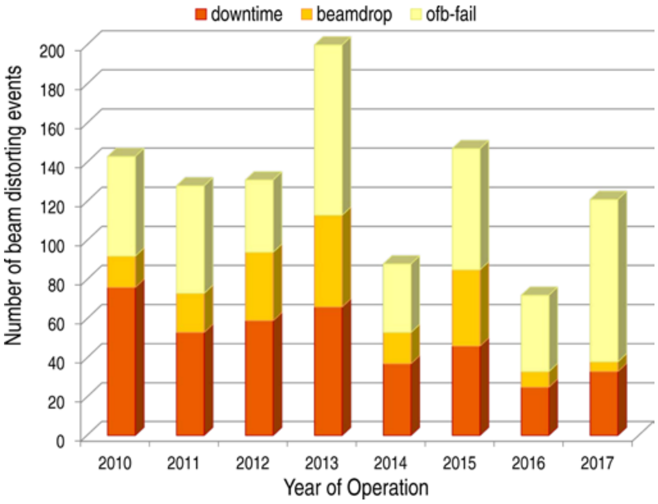

Figure 7: Number of beam distortions at SLS of the past years.

Figure 6 shows the number of beam outages of the past years grouped by failure categories. The total number of beam outages was again very low, only slightly higher than in the best year so far 2016. The RF had the lowest number of failures of all times. It is worth noting that the number of beam losses from unknown failures remains rather constant on a high level. This year those failures caused more outages then any other failure category. The planned new BPM system with a fast orbit diagnostics could help to locate the root cause for these.

Figure 7 shows the numbers of different events for the past years that contributed to the Mean Time Between Distortions (MTBD). The number of beam interruptions was low, but the number of beam-drops has been the lowest in the history of the SLS, again. The orbit feedback outages on the other hand were slightly higher than the past years. The resulting MTBD was 42 hours.

Figure 8 shows that the largest fraction of beam outages in 2017 was from the vacuum – mainly from the above mentioned water

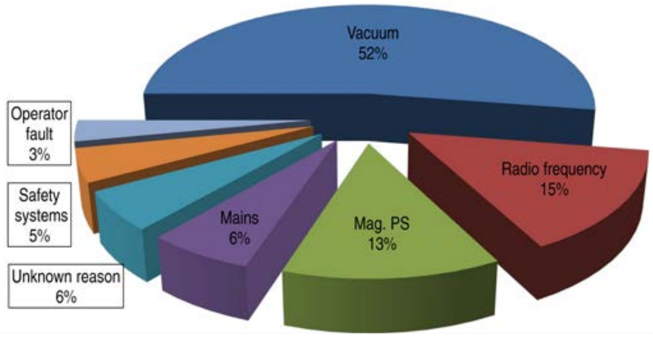

Figure 8: Beam outages per failure category in 2017 at SLS.

leak in the absorber. Three new absorbers have been produced; two were installed as replacement for the broken ones and one spare. A new position has been opened for the maintenance of the frontends. A redesign of the absorbers will be done in the context of the upgrade project SLS-2. RF failures contributed with only 15%, an excellent value compared to other facilities. The 13% outages from magnet power supply failures is a good value, considering the large number of magnet power supplies installed in the SLS. Table 2 summarizes the SLS operation statistics.

Table 2: SLS Operation Statistics

Beam Time Statistics	**2017**		**2016**	
Total beam time	6784 h	77.4%	6864 h	78.1%
• user operation	5048 h	57.6%	5016 h	57.1%
- incl. compensation time	184 h	2.1%	160 h	1.8%
• beamline commissioning	792 h	9.0%	800 h	9.1%
• setup + beam development	944 h	10.8%	1048 h	11.9%
Shutdown	1976 h	22.9%	1928 h	21.9%
User operation downtimes	30		25	
• unscheduled outage duration	63 h	1.3%	45 h	0.9%
• injector outage (non top-up)	1 h	0.0%	1 h	0.0%
Total beam integral	2528 Ah		2497 Ah	
Availability	98.7%		99.1%	
Availability after Compensation	102.5%		102.4%	
MTBF	163 h		193 h	
MTTR (mean time to recover)	2.1 h		1.8 h	
MTBD (mean time between distortions)	42 h		67 h	

SwissFEL

After the successful inauguration of the facility in December 2016 – with free-electron lasing demonstrated for a photon wavelength of 24 nm, achieved with beam energy of just 345 MeV – the year 2017 was dedicated to the further development of the facility to a level where first pilot experiments would be possible. Indeed, the successful execution of the first time-resolved pump-probe experiments in the two available experimental areas represented the prime objective of the project management for that year. This implied, in particular, a substantial increase in electron energy, to a minimum of 2.5 GeV, to reach photon wavelengths of interest to the experiments (0.54 nm, corresponding to photon energy of 2.3 keV).

The year started with a two-month long shutdown for remaining installation work. In March the full acceleration chain of the injector (S-band frequency, 3.0 GHz) could be brought into operation, delivering the nominal beam energy of 350 MeV for that part of the accelerator. The X-band cavity (12 GHz), needed for phase-space manipulation before the first bunch compression unit, became available in May, allowing first beam physics tests with systematic compression.

In parallel the C-band (5.7 GHz) RF stations of the Linac were prepared for beam operation. By mid May three such RF stations were available for acceleration, allowing for the first time lasing in the X-ray range. With a beam energy of 910 MeV the achieved photon wavelength was 4.1 nm, well in the soft-X-ray regime. The photon pulse energy, measured by means of a gas ionization detector was around 30 µJ.

After the connection of more RF modules in two brief shutdowns in June and August, it was possible to reach a beam energy of 1.62 GeV by utilizing a total of six C-band RF stations. The resulting radiation, now at a photon wavelength of 1.28 nm, was harnessed for the first commissioning of photonics components in the optical hutch at the end of August.

In another one-month shutdown in September final installations towards the first pilot experiments were carried out, most notably waveguide connections for five more C-band RF stations and a crucial upgrade of the dose rate protection system. During October, the electron beam was prepared for efficient lasing at the required beam energy of 2.5 GeV. This included the setup of a laser heater for the mitigation of detrimental microbunching instabilities as well as the compression of the beam with two compression stages. After a test run in mid November for the setup and commissioning of the experimental areas, the first pilot experiments could be conducted as planned during two dedicated weeks at the end of November (experimental station Bernina) and in mid of December (experimental station Alvra), respectively. By the end of the year, 11 out of the planned 26 RF stations in the Linac were operational, providing a maximum beam energy of 3 GeV, more than half of the design energy of 5.8 GeV.