# PERFORMANCE OF THE PSI HIGH POWER PROTON ACCELERATOR

M. Seidel, A. Mezger
Paul Scherrer Institut, PSI, Switzerland

Email contact of main author: mike.seidel@psi.ch

**Abstract**. PSI operates a 590 MeV proton accelerator that drives a neutron spallation source and delivers a high average beam power of up to 1.3 MW. In 2008 the Ring Cyclotron, which represents the major component in the accelerator chain, was upgraded by installing the remaining two out of four new and more powerful accelerating resonators. This paper describes the performance of the facility achieved with these new resonators in terms of beam power, grid-to-beam power transfer efficiency, beam losses and activation, statistics of beam trips and run durations as well as overall reliability.

## 1. Introduction

The PSI High Intensity Proton accelerator consists of a Cockroft Walton pre-accelerator and a chain of two cyclotrons. It produces a continuous-wave (CW) proton beam with a bunching structure of 50 MHz. The final beam energy is 590 MeV and the beam current was just raised from 2.0 mA to 2.2 mA for standard operation in 2009. Consequently the beampower amounts to 1.3 MW and as of today this represents the highest average beampower generated in any accelerator. With such parameters the cyclotron based accelerator concept presents a possible alternative to linac based systems for ADS applications, where a high power CW beam is required as well.

At PSI the beam is used to produce pions and muons by interaction with two graphite targets that are realized as rotating wheels. At the second target with a thickness of 40 mm a fraction of 30% of beam current is lost because of nuclear reactions and Coulomb scattering in combination with subsequent collimation. The remaining beam is then used to produce neutrons in a spallation target that contains lead filled Zircaloy tubes. The research performed at PSI covers a broad range of applications and involves neutron scattering experiments, muon spin resonance spectroscopy and a few particle physics experiments. Fig. 1 shows an overview of the accelerator facility including the secondary beamlines.

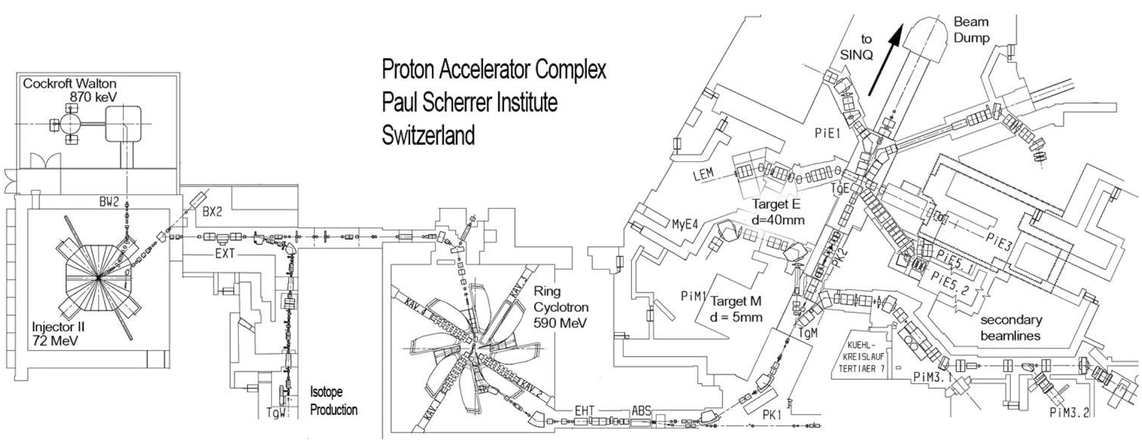


*FIG. 1. Top view of the accelerator facility at PSI. The outer diameter of the Ring cyclotron amounts to 15 m.*

The original PSI accelerator started operation in 1974. Since then many small improvements but also several major modifications made it possible to significantly raise the beam current to the levels routinely operated today. The maximum beam current in the accelerator is and was always limited by the beam losses. The important losses occur at the extraction in the Ring cyclotron. Protons that are scattered in the electrode of the electrostatic extraction element are lost in the extraction beamline and cause activation of accelerator components. The maximum acceptable activation levels are in the range of a few mSv/h. Practical experience shows that such levels are not exceeded over longer times if the beam losses are kept in the range 200-500 nA. The history of the operating beam current in the PSI facility is shown in Fig. 2. Despite the significant increase of the intensity the absolute losses have been kept within the range mentioned before. In other words, the relative losses were continuously decreased and reached a level in the lower $10^{-4}$ range. Typically the accelerator is operated 9 months per year, starting in April through the holidays in December. In section 2 of this paper we discuss the power conversion efficiency and intensity limiting effects. Section 3 concentrates on the reliability of the facility, which is an essential aspect when the application of cyclotron based high power accelerators for industrial purposes, e.g. ADS systems is considered.

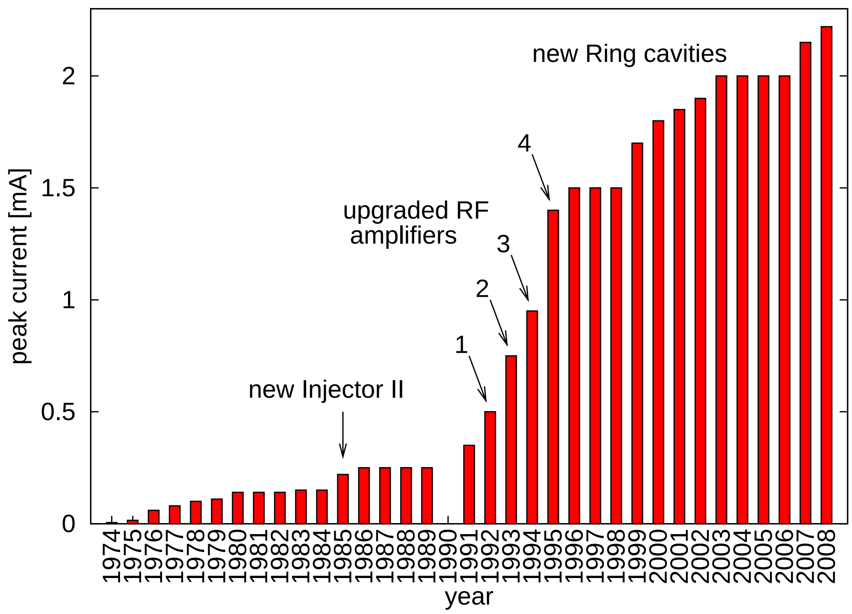


*FIG. 2. History of the maximum beam current achieved in the cyclotron based PSI facility.*

## 2. Power Transfer, Maximum Beam Power and Limitations Thereof

For the application of neutron production a high beam power is most important to maximize the neutron flux. Under the constraint of constant beam power the rate of spallation neutrons is not a strong function of beam energy above 600 MeV [1]. Consequently the obvious upgrade path for the facility is a stepwise increase of the beam power. In the context of potential ADS applications the efficiency for the conversion of grid power to beam power is of interest. At the PSI facility this question is not easily answered because many magnets and other auxiliary systems that contribute to the power balance are not needed for the basic accelerator operation, but for secondary experimental facilities. In the transfer line to the SINQ spallation source the beam is deflected vertically several times by huge and power consuming magnets to enter the target in vertical direction. The total power consumed in the facility at zero beam current but with magnets and RF systems in operation amounts to approximately 8 MW. For an optimized ADS system this base level could be lower. It is possible to measure the total PSI-wide power consumption as a function of the beam current.

This method allows measuring the differential grid-to-beam efficiency around the working point of 2 mA. An example is shown in Fig. 3. The slope of the curve represents the differential power consumption per mA of beam current, and for this measurement it was determined as 0.81 MW/mA. On the other hand the kinetic beam energy of 590 MeV determines the power the beam carries as 0.59 MW/mA. The ratio of the two numbers gives us the differential conversion efficiency of wall plug power to beam power and it amounts to 73 %.

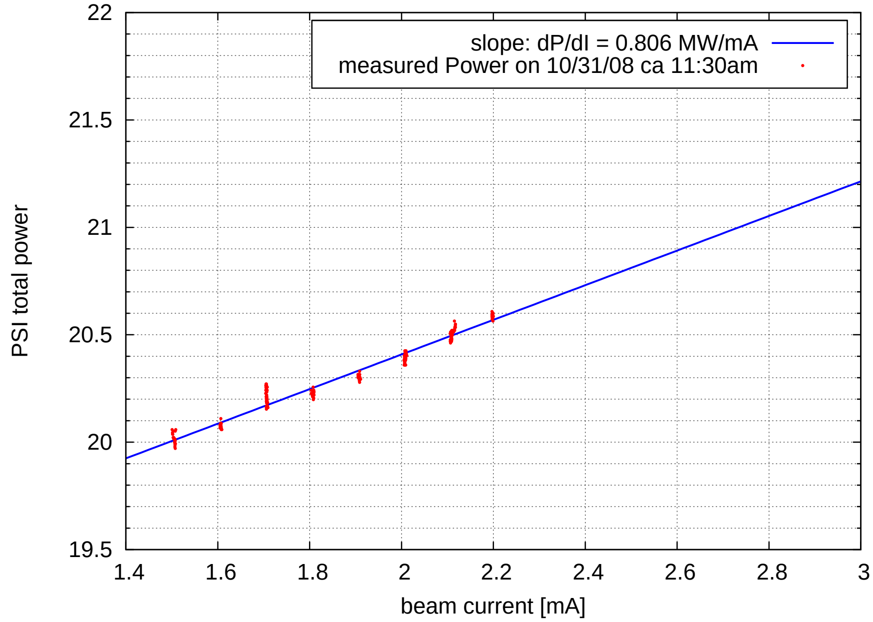


*Fig. 3: Measured total PSI power as a function of proton beam current. Note that the proton accelerator uses roughly 10 MW, the remaining power is used by other accelerators and the PSI infrastructure.*

The maximum beam power in the PSI facility is in fact not limited by the power transfer from the grid, or the performance of the RF system. In practice the limitation is given by the beam losses that cause activation and more indirectly the radiation dose the technical personnel receives during maintenance work on accelerator components. Over the long term history of the accelerator the typical collective radiation dose received by the personnel during maintenance works and modifications of the accelerator was continuously decreased [2]. This was mainly achieved by optimized handling of activated components and the introduction of specifically customized mobile shielding, or transportable shielding devices for critical components.

In view of activation the critical components in a high power cyclotron are the extraction elements. An electrostatic deflector channel deflects the beam in the last turn by 8 mrad, which then allows to extract it from the cyclotron using a magnetic septum. The inner electrode of the electrostatic element is made from 50 μm tungsten foils, and those are placed between last and second last turn. Protons in the beam tails may hit the tungsten foils and as result of scattering and energy loss these particles are separated from the beam core and hit components in the extraction beamline. The activation levels in this region amount to several mSv/h [3] with a local peak value of 9 mSv/h. Under optimized conditions the losses in the extraction beamline are at the level of $2{\cdot}10^{-4}$ relative to the total beam current. This is to be compared with typical losses of 20% to 50% in traditional low power cyclotrons, as they are used for medical applications. In order to keep such losses at a minimum the generation of beam tails from space charge effects is minimized in combination with maximizing the turn separation on the outer turns. With a simple qualitative argumentation Joho [4] has shown that the extraction losses are a strong function of the number of turns in the cyclotron, and in fact they scale with the third power of the turn number. The installation of new Cu resonators in the PSI Ring cyclotron in 2008 made it possible to raise the accelerating gap voltages and to reduce the number of turns from 202 to 187. This led to a significant reduction of the extraction losses by a factor of roughly 2. Fig. 4 shows the dependence of the extraction losses on the beam current. The losses are measured with ionization chambers that are calibrated by purposely arranging a complete loss of a very small beam current. The data is taken from normal operation periods during which the accelerator was operated most of the time at 2.0 mA. Consequently the accelerator was better optimized at this current. Nevertheless the non-linear rise of the losses, caused by space charge effects, is clearly visible.

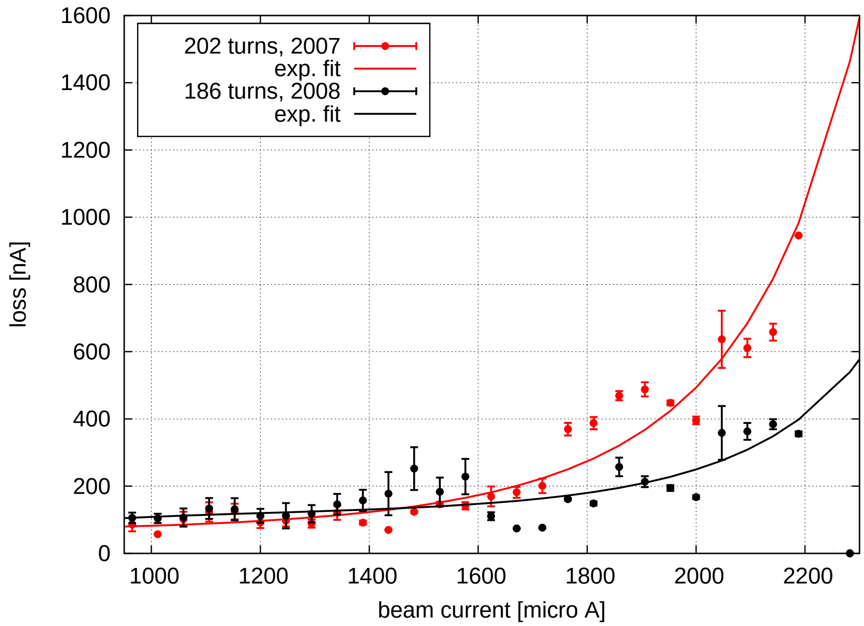


*FIG. 4: Scaling of the minimum beam losses as a function of current. Since the accelerator was operated most of the time at a current of 2 mA, the data points are sampled in a non-uniform way.*

## 3. Operational Statistics and Reliability

The utilization of a particle accelerator for transmutation purposes requires extremely reliable operation of the facility. Beam trips cause thermal cycles for the fuel elements which may lead to fatigue failure. In this context we present here a statistical analysis of the practically achieved accelerator trip rate in the PSI facility, specifically the distributions of recovery times and uninterrupted run times. For longer interruptions we present in addition data on the subsystems that caused the interruptions.

Most of the short term interruptions in the cyclotron are caused by high voltage trips of the electrostatic elements which deflect the injected and extracted beams. Other causes are occasional triggers of the interlock system by spikes in the lossrates, or trips of the RF system. In most cases the system that originated the interruption is automatically reset and the current is ramped up again within 30 seconds. In order to quantify the trip statistics we have analyzed the run periods in 2007 and 2008. The above mentioned reduction of the turn number in the

Ring cyclotron from 202 to 187 turns in 2008 resulted in a significant improvement. So we consider here the period after this change, which includes 165 operation days with a total of 3.478 trips. In 2007 the considered time amounts to 254 days with 15.593 trips. Histograms with the probability distribution of run durations and trip durations were computed. It is difficult to read practical information from such histograms since the number of events in a bin depends on the bin width. A better way to present the data is therefore to integrate the histograms in the following way:

$$N_{r,i}\left(t > t_{r,i}\right) = \int_{s=t_{r,i}}^{\infty} n_{r,i}(s)\,ds\,.$$

Here $t_{r,i}$ is the duration of a run resp. interruption period and $n_{r,i}$ is the number of such events that falls into a certain interval [$t_{r,i}$, $t_{r,i}$ +$dt$]. The resulting number $N_{r,i}$ gives the number of events with a duration longer than the value read from the abscissa (Fig. 6, Fig 7). At the very left end of the graph one can read the total number of runs and interrupts per day. Clearly the total number of runs and interrupts equals, however the shape of the distributions as a function of duration does not. The probability of having interruptions scales roughly inversely with their duration time. It can be argued that this is caused by the fact that retuning or repair work is being started as soon as a failure situation is recognized by the operators, and the probability of such attempts to be successful is increasing linearly with time. On the other hand the duration of the run periods is given by the first failure situation occurring in one of the many accelerator components. The times between failures of single components are often exponentially distributed and one observes a summation of many of such contributions.

The overall reliability of the PSI accelerator, defined as the ratio of delivered and scheduled run time, is relatively good in comparison with other high power accelerators. Over the past years the average reliability was 90%. In the second half of 2008, after the performance upgrade, a value of 94% was achieved. The total trip rate is now roughly 20 $d^{-1}$ versus 60 $d^{-1}$ in 2007 (see Figures). However, it has to be stated that this performance is still more than 3 orders of magnitude away from the trip rate which is presently being postulated for ADS applications. For serious ADS application the anticipated trip rate is around 0.01 $d^{-1}$ [5]. In Fig. 7 the corresponding curve for a hypothetical accelerator with this performance would start with a value of 0.01 $d^{-1}$ on the left side and show a fall-off only beyond 100 d, i.e. 2.400 h. Several improvements to increase the reliability are imaginable and are mentioned in the next section. However, it seems to be very difficult to achieve an improvement factor of three orders of magnitude. Possibly a re-evaluation of the requirements on the target side is required as well, to make the design of an ADS system feasible.

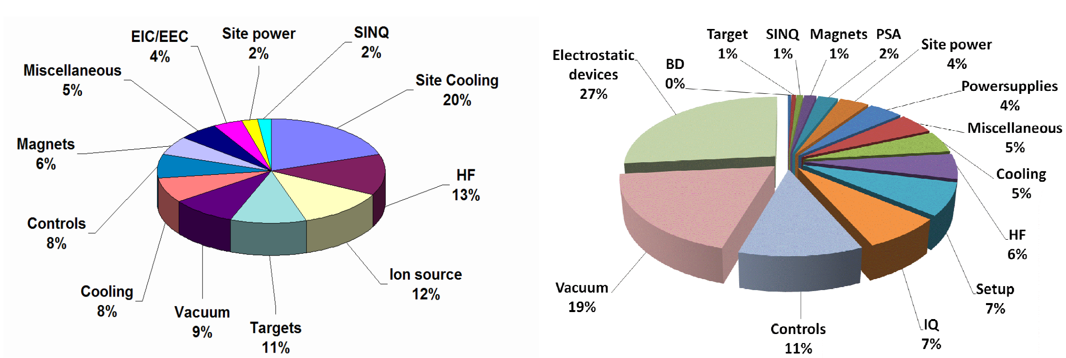


*FIG. 5: Causes of interruptions with durations longer than 5 minutes for 2007 (left) and 2008.The percentage values are relative to the total downtime.*

The classification of failures that cause interruptions longer than 5 minutes is shown in Fig. 5 for the years 2007 and 2008. Some prominent downtimes are caused by subsystems that have long repair times, such as site cooling failure or vacuum leaks. In 2008 both electrostatic devices in the Ring cyclotron (EIC/EEC) had to be exchanged, whereas in 2007 only minor problems occurred with these devices.

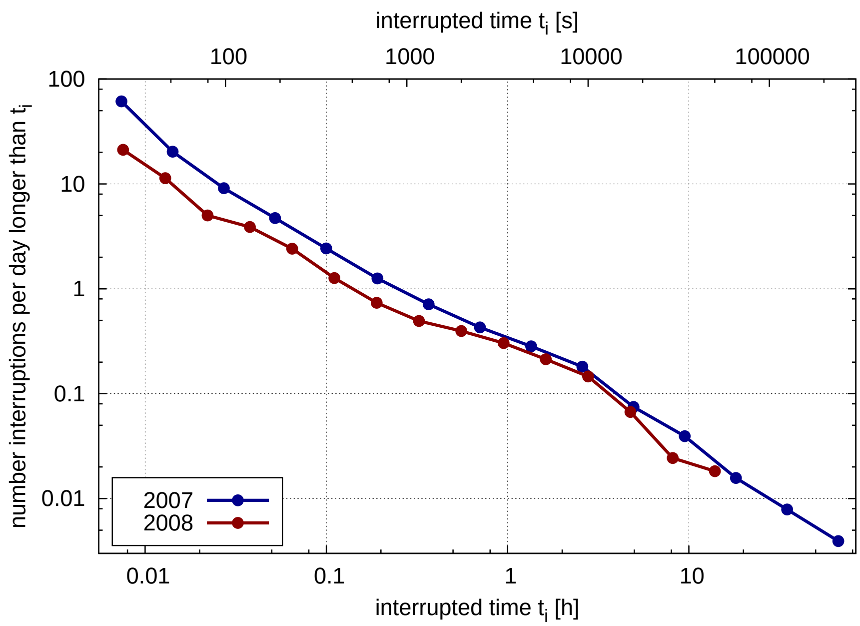


*FIG. 6: Integrated histogram showing the number of interruptions per day as a function of their duration.*

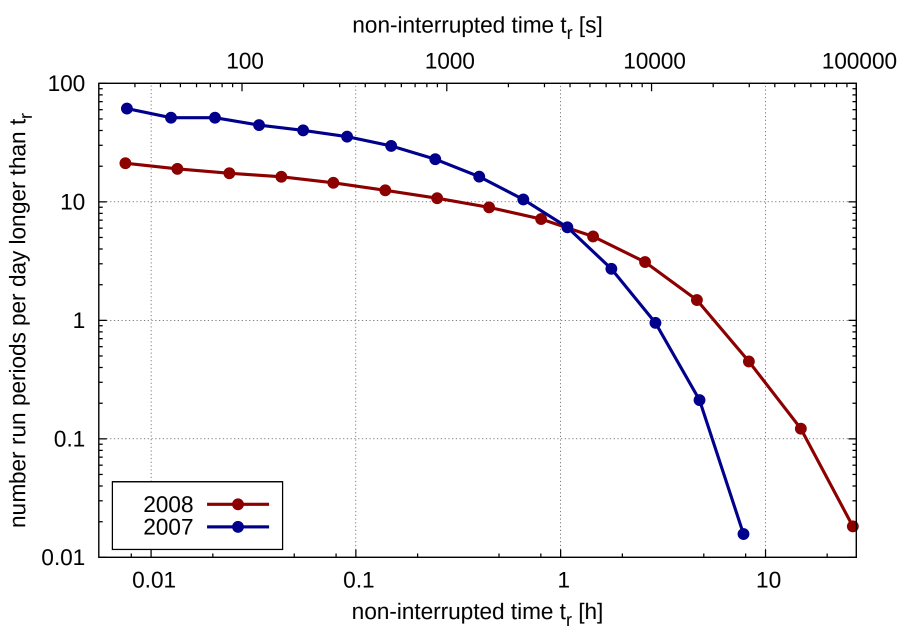


*FIG. 7: Integrated histogram showing the number of run periods per day as a function of their duration.*

## 4. PSI Upgrade Plans and Discussion on High Power Proton Beam Applications

At PSI a program is under way to further increase the beam intensity to an ultimate level of 3 mA/1.8 MW. After the Ring cyclotron has been equipped with more powerful resonators also the injector cyclotron will be upgraded with two additional accelerating resonators. The resulting reduction of the turn number will allow also in this case to reduce the losses and to produce a qualitatively better beam [6]. Other measures include the installation of a 10´th harmonic buncher between injector and Ring cyclotron, which will improve the beam quality in the Ring cyclotron, and the installation of beam absorbers with improved cooling.

If a PSI type high power proton accelerator was to be considered as a driver for an ADS system, which aspects should be improved for such application? For higher beam power, for example 10 MW, the relative beam losses have to be reduced further. This can be achieved by even faster acceleration in the main cyclotron in combination with a moderately larger extraction radius. In reference [7] a proposal has been worked out for a 1 GeV/10 MW cyclotron accelerator, based on similar principles as the presently operating PSI cyclotron. The proposed cyclotron employs 8 resonators with peak gap voltages of 1 MV. The required number of turns would be around 140. Because of relativistic effects the energy of 1 GeV seems to be the ultimate limit for an isochronous cyclotron. There is no fundamental limit for the beam power, although at some point technical challenges will arise from limitations in the power couplers of the accelerating resonators.

The second most important aspect concerns drastic improvements of the reliability and lowering of the before discussed trip rate. Large turn separation at the electrostatic elements will improve their trip rate. Since short beam interruptions below 1 sec can be ignored in view of thermal cycling of the target, another possible measure is to recharge the electrostatic elements very quickly after a trip. Fault tolerance against RF trips can possibly be achieved by an automated redistribution of the RF power, thereby guaranteeing a constant integral gap voltage even when a single resonator fails. The mentioned proposal from 1996 was not specifically optimized in view of fault tolerance. The design can likely be improved in this respect by the employment of more resonators. Space can be gained by using stronger but shorter dipole magnets and by slightly increasing the radius. At RIKEN/Japan a cyclotron has been built using superconducting sector magnets with a field strength exceeding 4 T [8].

Overall advantages of the cyclotron concept are given by the compactness of the accelerator, the high efficiency of the power transfer from grid to beam and effectiveness in the sense that only a few resonators are needed to transfer the total power to the beam.

## 5. Summary

In this paper we discussed the performance of the PSI high power accelerator with special emphasis on a possible application of such cyclotron based facilities for ADS systems. With 1.3 MW power at a beam energy of 590 MeV the facility has reached a respectable performance which is already within the useful range for ADS. However, the observed reliability and trip frequency are still 3 orders of magnitude worse than the values that are desirable for ADS. These aspects could be improved by implementing several measures. Nevertheless, one may have doubts whether the desired trip rate of $0.01\ d^{-1}$ can ever be reached with any type of accelerator. In this context it will be helpful to re-evaluate this extreme requirement carefully and possibly implement more tolerant target systems. As next step in cyclotron development the design of a facility that provides a 1 GeV/10 MW beam with improved reliability seems feasible.

**References:**


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