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SINQ as of 1998 (Status Report)

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Abstract

the Swiss spallation neutron source SINQ had first beam on target on Dec. 16, 1996 and reached its full current of 0.85 mA on the following day in a demonstration run. After a commissioning phase during the first half of 1997, in which the parameters of the source were studied, full current operation was resumed in the second half of the year with no technical problems. The first half of 1998 was characterised by an extensive accelerator shut down in which the splitter region that supplies beam to PSI's medical facility was completely rebuilt and which advantage was taken of by SINQ to open up two previously blocked beam ports for new instruments and to carry out the first target exchange. The user programme will start in July 1998 and by the end of the year it is expected to have 12 experimental facilities operational with five more under construction.

1. Introduction

SINQ at the Paul Scherrer Institut in Switzerland is the latest member in the family of operating spallation neutron sources. Being an add-on to an existing accelerator, a 590 MeV cyclotron, there was no choice on the time structure. Therefore SINQ is a continuous neutron source and hence plays in the competitive league of research reactors. Like a modern research reactor, it has a large D_2O tank where the beam tubes originate (Fig. 1) and is designed to permit access to the outside of the target biological shielding on all sides. This is accomplished by injecting the beam into the target from underneath; another feature which makes SINQ unique among its (unfortunately few) fellow spallation neutron sources.

Over the course of the years the beam current of the PSI ring cyclotron has been upgraded from its original design value of 100 μA to 1.5 mA, which makes this the world's highest time average proton current. Since the prime purpose of the accelerator used to be pion and muon generation, there are two targets in the beam upstream of SINQ, of which in particular the last one, "Target E", has a strong effect on the phase space distribution in the beam. After scraping the generated halo and reshaping and focusing the beam for further low loss transport, only 0.85 mA at 570 MeV are left to drive SINQ. Nevertheless, this is a serious power level to deal with and, in anticipation of future improvements, the SINQ target and its heat removal system have been

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designed to handle 1 MW of beam power. During the design studies it was concluded that, in order to remove this power from a solid target and to avoid excessive stress which would shorten the life time unduly, a rod structure of the target and a hemispherical beam entry window were the best solution. Since its first day, SINQ has been operating on a target made up from 450 Zircaloy-2 rods of 10.8 mm diameter, arranged in a closely packed array with a pitch of 1.2 and cooled in a cross flow configuration. Since the neutronic performance of this target is not optimum, a development program is going on that aims at achieving a gain factor of at least two from using a higher yield target material. Several reports dealing with this work can be found in these proceedings.

2. SINQ - The Worst of Both Worlds or a Breakthrough?

"The worst of both worlds", this was the comment made when the then SIN (Swiss Institute of Nuclear Research) announced the intention to build a continuous spallation neutron source - meaning that this facility would suffer from the disadvantages but not benefit from the potential advantage of a spallation neutron source over reactors: the pulse structure.

Now, while the pulse structure is clearly missing, there are other advantages of spallation neutron sources that SINQ shares: the absence of criticality, the ease of shutdown in an emergency, the lower γ-ray production per neutron (and hence better conditions for cold moderators close to the primary source), the lower afterheat, etc. These features make it well worth-while to think about continuous neutron sources in the future which work on a beam power level pulsed sources will simply not be able to handle because of their very pulsed nature. In this sense, SINQ is a breakthrough: It is proof that continuous spallation neutron sources can be built and operated and can be competitive with research reactors. Of course, during the whole construction phase the question was in the air: "will we be able to control the fast neutron background?" Now, after half a year of experience at full beam power we know: we were! The overall radiation level in the SINQ target and neutron guide hall is as low or lower than on any reactor and our cold neutron beams are literally free of high energy neutron contamination. It is true, that special care was taken to accomplish this in designing the system and in assembling the shielding, but the success shows: it can be done. Also high energy neutron contamination in the beams did not turn out as a problem. Probably three design features of SINQ contributed to this:

a) The plane is which all beam tubes are located is perpendicular to the proton beam; in this way the more forewardly emitted high energy neutrons are not seen.

b) Within a distance of 1 m around the target no materials (such as steel or heavy metals) are located that would strongly interact with high energy neutrons and lead to large angle scattering.

c) The axes of the beam tubes and neutron guides are displaced by 25 resp. 40 cm from the proton beam axis and grazing incidence of high energy neutrons directly from the target into the beam tubes is much less likely than in pulsed spallation sources where this distance is of the order of 10 cm only. All taken together, we are happy to state that SINQ is much less severely hit by the worst of the spallation source world than one might have feared before trying.

SINQ is a breakthrough also in that sense. It is also a breakthrough in that almost its whole neutron guide system is built from supermirrors. It was clear from the very beginning that the emphasis of SINQ would be on cold neutrons. This was not only because a cold source could be placed more optimally in the reflector of a continuous neutron source than in that of a reactor; this is also because long wavelength neutrons have shown a steady growth in importance in the field of neutron scattering and continue to do so.

Besides their scientific merits cold neutrons also have the advantage that they are easy to transport over long distances in neutron guides. Development of efficient neutron guides was, therefore, an important part in the SINQ project and it was done successfully: all glass plates for the neutron guides of SINQ were coated with supermirrors in PSI's own facility following a recipee developed here. They were then individually examined for quality and were sorted such that poorer plates would not jeopardize the performance of those guides where the large beam divergence supermirrors provide was useful. In sorting the glass plates the future use of the guides were carried in mind. For example, the SANS instrument with its narrow collimation does not need high angles of total reflection on the guides. (Since the extra neutrons would only be a nuisance when they generate γ-rays upon absorption, the SANS guide is actually the exception to the supermirror rule at SINQ). Also other high resolution instruments with primary collimation cannot use the full divergence of an m=2 guide and the less perfect plates were used for those. It should be noted, however, that, since the angular divergence is proportional to wavelength, an important advantage of supermirror coating is that it shifts the cutoff wavelength of a guide with a given curvature and width to shorter wavelengths. Fig. 2 shows a spectrum measured at one of the SINQ guides. Relative to predictions made during the construction phase (curve C), this guide has about 50% more intensity in the long wavelength region and shows a spectral shift of about 0.5 Å to longer wavelengths at the short wavelength side. These two properties are attributed to uncertainties in predicting the performance of the cold moderator, which, in the case of SINQ, is a large liquid D_2 volume [1]. In the region below 6 Å the rugged appearance results from Bragg edges of the materials in the beam (Zircaloy-2 and Aluminum). Despite this "depression" one would expect to be able to fit the curve with a Maxwellian distribution, making allowance for the total transmission also shown in the figure. This turned out not to be possible; in fact a sum of three Maxwellians was required to obtain a reasonably good fit (curve 3M); the best fit found for two Maxwellians is represented by the curve labeled 2M. A detailed discussion of the spectral and intensity measurements carried out during the commissioning phase of SINQ may be found in ref. [2]. A direct comparison, also made in that paper, showed that even where the supermirrors don't help, namely in the SANS instrument, SINQ performs equally well as a recently upgraded 10 MW reactor.

An overview of the neutron currents measured at the various monochromator or sample positions of different instruments and other locations is shown in Fig. 3. Except where a narrow collimation or wavelength band or multiple gaps in the guide reduce the intensity, values between 2.5 to 3.2 x 10^8 $cm^{-2}s^{-1}mA^{-1}$ are found for the guides and around 10^8 for the beam tubes. These data are for 1 mA; presently only 850 μA are available (see below). The contamination with neutrons above 20 MeV measured with the ^{12}C (n2n) reaction was less than 10^{-4} in the thermal beams and not detectable at the neutron guides.

3. A Furious Start and a Slow Takeoff

SINQ holds a record not only for being, by a large margin, the world's most powerful spallation neutron source; also the speed at which it went from first beam on target to full power is unbeaten: on Dec. 6, 1996 the beam line between target E and SINQ was first tuned with protons at a current level of 20 µA. (This is also when the first neutrons generated were used to measure the ToF-spectrum shown in Fig. 2). Little more than 24 hours later the source had reached its full power and had exhausted the contingent of 2 mAh set by the licensing authorities as the charge limit for this first demonstration run.

Clearly, it was never intended to take off at full power from that moment on, because several weak points in the shielding that had been left until the amount of shielding necessary could be determined by measurement, needed to be fixed and other parameter studies had to be made to fully understand the system. Therefore, a three months commissioning phase at varying current levels had been planned to take place after the end of the annual accelerator shutdown in the first half of 1997. During that time also the first generation instruments were completed and commissioned at low intensity.

Following this, full power operation was to be scheduled according to demand. As can be seen from Fig. 4, this demand rose continuously during the second half of 1997, but problems with a beam splitter upstream in the proton beam line became more and more serious and the delivered beam fell increasingly behind the scheduled one, ending up at a total of 500 mAh in 1997. In order to cure the problem with the beam splitter, which supplies protons to the medical facility for treatment of human cancer patients, an extensive shut down was scheduled for the full first half of 1998. The splitter region was completely rebuilt and an new concept for the splitter was used. The hope is that, after restart at the beginning of July 1998, these problems will be solved and routine operation of SINQ will start. Apart from changing the target, the shutdown period was also taken advantage of to implement the overall control system which should allow the SINQ target station to operate without the control room being manned. This is a necessary condition for being able to come close to the goal of 140 days of running at full current in the second half of 1998.

Although there is clearly still some uncertainty attached to the SINQ schedule in the second half of 1998, a call for proposals was launched in February 1998 for those instruments that would be operational when the source restarts or would be completed during the rest of the year. Proposals for short term experiments as well as long term research programs were solicited. The result shown in Table 1 is very rewarding on the one hand but very obliging on the other. For SINQ to become a competitive player in the league of continuous neutron sources in Europe, we must achieve high availability and further improve the performance of the source. At the same time, more instruments will come on line. Apart from the neutron scattering instruments listed in Table 1, for which proposals have been solicited, SINQ currently hosts several other neutron facilities which will become available for users soon:

- a thermal neutron transmission radiography facility
- a cold neutron capture radiography facility
- an isotope production station
- a facility for neutron activation analysis
- a facility for prompt gamma emission studies
- a facility for fission product studies, using a thin uranium foil in the thermal flux.

Further instruments under construction or in the planning stage are
- a polarized neutron decay instrument (particle physics)
- an engineering strain scanner
- a high resolution crystal analyser time of flight spectrometer
- a phase space transformer for high resolution thermal neutron time-of flight

This large investment into the source utilization adds even more to the pressure to improve the performance of the source itself.

Table 1:

	Short term proposals		Long term proposals	
Instrument	Total days available	Total days requested	Total days available	Total days requested
AMOR (Reflectometer)	not sched.			
DMC (Cold n diffract.)	15	71	83	137
DrüChaL Cold n TAS)	31	56	167	228
FOCUS (cold n ToF)	0	38	49	126
HRPT (high res. Powder)	0	15	100	141
SANS (small angle scatt.)	21	55	147	375
TASP (pol. n TAS)	22	121	149	295
TOPSI (Test beam)	-			10
TRiCS (4 circle diffr.)	0	-	100	98

4. The Way to More Neutrons

For SINQ, the number of useful neutrons generated per unit time depends on four main factors:
- the average availability of the accelerator (currently > 85%)
- the fraction of the accelerator up time during which SINQ can receive beam (in competition with other modes of operation)
- the fraction of beam lost in the target E
- the neutronic performance of the SINQ target.

As for the availability (mAh delivered / mAh scheduled) of the accelerator, the current value of more than 85% includes, of course, periods where some problem anywhere along the beam line impedes operation. Transporting a 1.5 mA beam with low losses along most of the beam line is not trivial. Even the target "E", which is a 6 cm long rotating and radiation cooled graphite ring and never used to cause problems, now must be replaced about twice a year because it deforms due to radiation damage. So, while some improvement may be possible, one will always have to be prepared to accept a certain amount of time lost. Even on good days, i.e. without major beam interruptions the users will be faced with and will have to adjust to a large number of short trips. An example of such a day is shown in Fig. 4. Although the beam delivered was 97% of what could be expected, many short interruptions occurred, often lasting less than 1 minute (lines not going all the way down to zero in Fig. 4, where the sampling time is 1 minute).

As far as other operating modes of the accelerator are concerned, there were two types of "single use" at low current in the past: (1) If human patients were being treated at the proton cancer therapy station and the splitter did not work reliably, it became necessary to run the whole facility at low current with direct injection to the medical facility. This will, hopefully, be solved with the new splitter. (2) Some particle and nuclear physics experiments used polarized protons which could only be supplied at low intensity from a special injector. This program will also come to an end soon, as the number of users not served while it is running has become too large.

Concerning the fraction of beam lost at target E, the possibility of shortening that target from 6 to 4 cm has been studied [3]. While some of the pion and muon experiments would not suffer from that move, others would lose 1/3 of their present flux. For SINQ it would, by the same token, mean a 50% gain, but would also require different tuning of the beam transport line, which can probably be done. Currently this issue is still being debated, but another development might make this move even a must: The accelerator group is looking into using copper cavities instead of the present aluminum cavities, which might allow to operate the accelerator at 2 mA. If this materializes, Target E must be shortened to keep the power deposition and activation from the lost beam in its environment at the present level. In this case the total gain for SINQ would be almost 70%, raising the beam power to over 800 kW (this is why the design power is 1 MW).

Finally, as far as the target itself is concerned, theoretical studies [4] showed that, in the optimum case, a factor of 2.7 in neutron yield could be gained if it was possible to realize a liquid lead-bismuth target of optimum thickness and with a low absorption container. Realistically a factor around 2.4 can be expected with a steel container. By improving the solid rod target through the use of clad lead rods - which is the more near term solution - the anticipated gain is about 1.6. Work towards this step is reported in other papers at this conference [5] [6] [7].

5. Conclusions

Since SINQ first became alive in Dec. 1996, it could be shown that the concept of a continuous spallation neutron source is not necessarily a stupid one. Its breadth of use ranging from isotope production and activation analysis via radiography all the way to high resolution neutron spectroscopy makes it competitive with existing research reactors and, in a different sense, also with pulsed spallation neutron sources. From the onset on the system performed well at full power and constituted a breakthrough in several respects. Especially the successful use of supermirror neutron guides, although not tied to any specific source type has opened up the possibility of designing for "all guide sources" in the future, also in the regime of thermal neutrons. Even, if these guides are designed without curvature, they would help to further reduce the high energy neutron contamination at the monochromator position significantly below the level of 10^{-4} relative to the thermal flux which is currently measured at SINQ. This would eliminate practically completely the worst of the spallation source world and would allow to take full advantage of the best of the continuous source world, namely that the neutron flux per unit proton current is high and that the distance over which neutrons can be usefully transported by guides is not limited by frame overlap considerations. In view of the limitations on pulse power that can, at present, be handled with confidence and in view of the need for non-diffractive uses of neutrons which rely on high time average flux, the successful operation of SINQ may well mark a real breakthrough, and its further development may show a route to the future.

6. References

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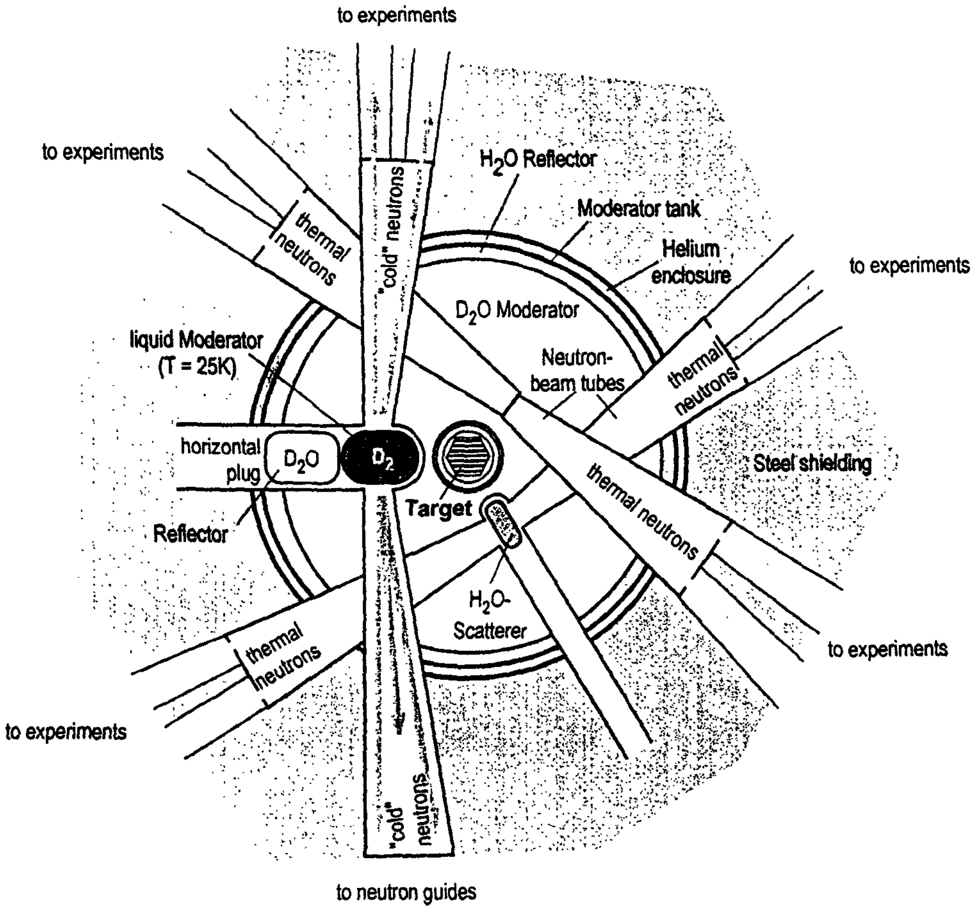

Figure 1: Schematic horizontal cut through the SINQ Target-moderator region

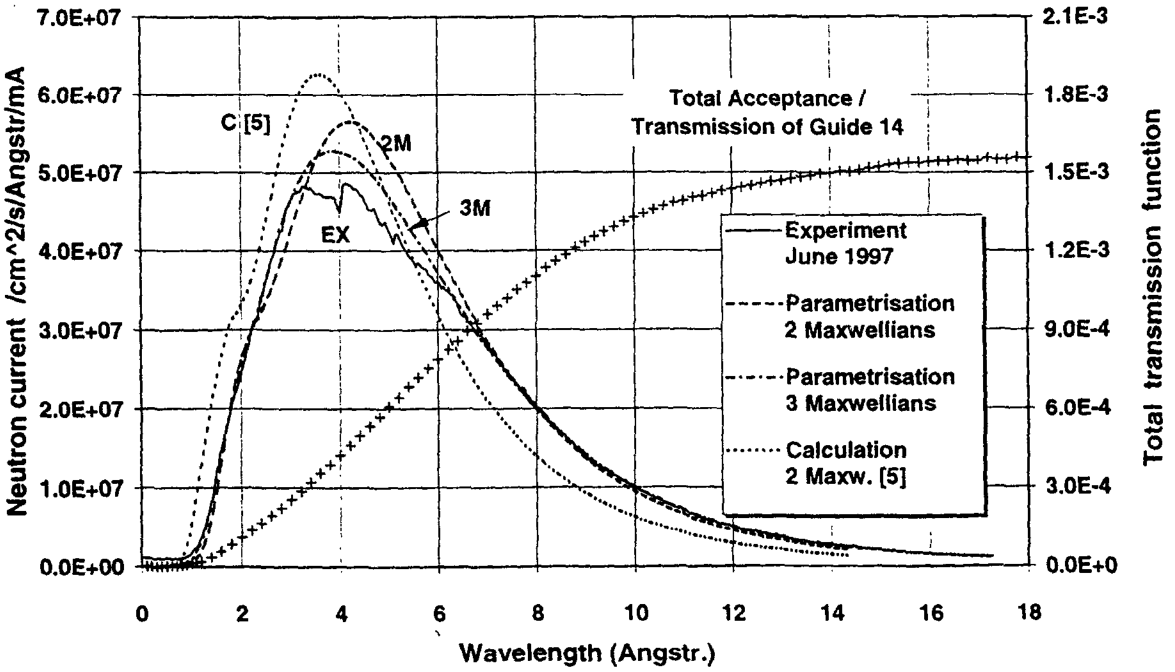

Figure 2: Cold neutron spectrum measured at the SINQ guide IRNR14 and calculated transmission function of that guide

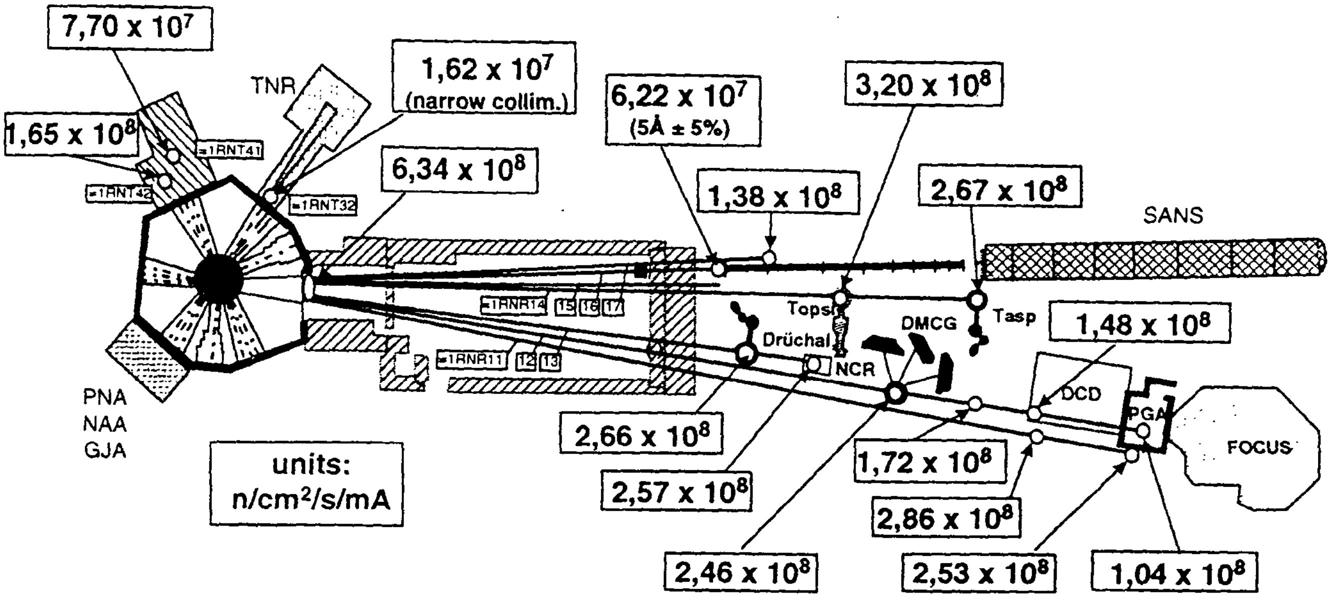

Figure 3: Measured neutron currents at various positions of the SINQ guide system and thermal neutron beams

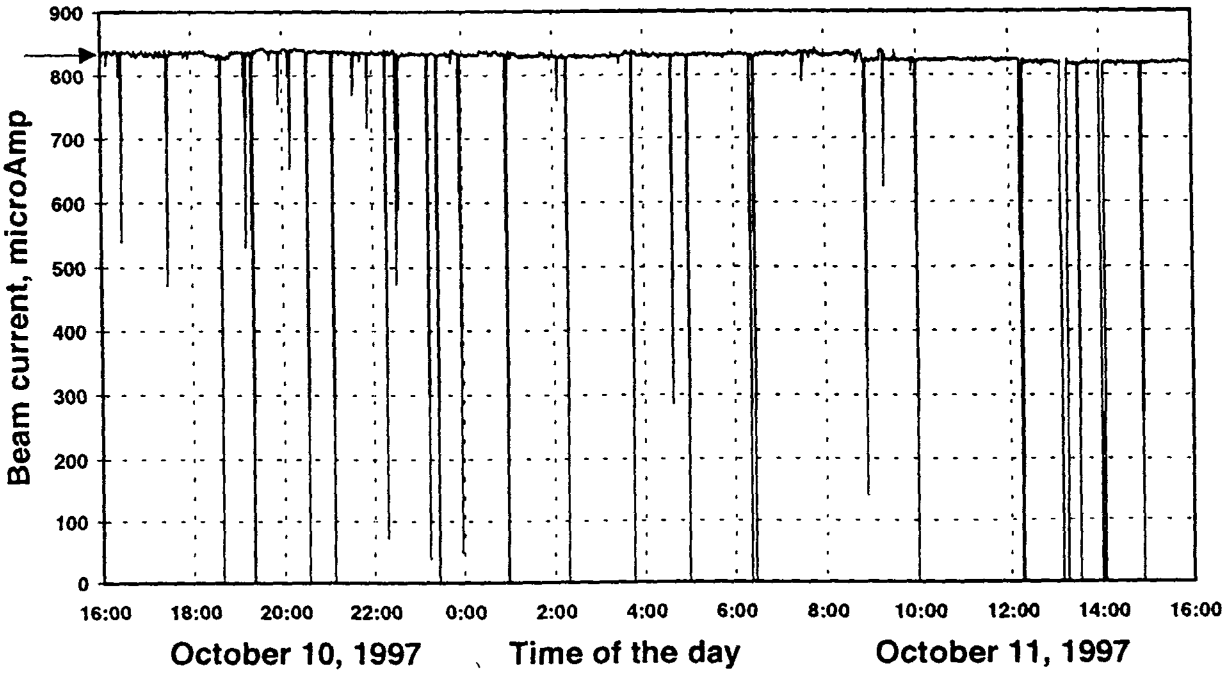

Figure 4: Example of the recorded proton current over a period of 24 hours with high accelerator availability but a large number of short trips. The total charge delivered during the period shown was 19.3 mAh; the integrated performance was 97.1 %.