ACCELERATOR RELIABILITY - AVAILABILITY

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Abstract

Following a pioneering period during which the major concern of accelerator physicists was to achieve the highest intensity as well as explore the largest range of energy, accelerators quickly became a tool at the service of a wide community. Accelerators started to be used for medical and industrial purposes. Now, a single accelerator can also serve a wide range of Users at the same time (X-rays sources). Reaching a high Mean Time Between Failure as well as high availability became a constraint for such Machines.
Various spallation neutron sources are upgraded. The idea of using them for transmutation processes or in the long term, to replace the conventional nuclear reactors, has now been comprehensively studied. Besides pure accelerator physics considerations, it is now agreed that the reliability of these accelerators must be drastically improved with respect to the present situation.

1 RELIABILITY: GENERAL CONSIDERATIONS AND DEFINITIONS

1.1 A brief history of reliability

First reliability models emerged during World War II. The goal was to make the rockets as well as radars more reliable. At that time, there was some confusion: reliability of electronic components (Random failures) was computed as for mechanical components (aging, overstress, etc). The late comprehension of this difference marked the beginning of redundancy /reliability models.

This methodology was not of concern for particle accelerator designers, despite the fact that, at that time, the first electron Linac had been around for 20 years, Van de Graaff had developed the first high voltage generator 10 years previous, cyclotron developments were well in progress, the first functioning betatron had been completed.

1.2 Some definitions and useful acronyms

Let us first review some words or acronyms that will be used extensively in this paper. Further comprehensive definitions can be found in [1].
- **Availability** represents the fraction of time during which a system meets its specification. A system must be designed for high availability when continuous service is important.
- **Reliability** reflects the probability that a system can perform its intended function for a specified time interval under stated conditions. A system must be designed for high reliability when the repair of its component is long.
- The **Mean Time Between Failure (MTBF)** is the mean number of life units during which all parts of a system perform within their specified limits, during a given time interval.
- The **Mean Down Time (MDT)**, the average time a system is unavailable due to a failure. This time includes the actual repair time plus all delays associated with the repair (finding the spare part, etc).
- The **Mean Time To Repair (MTTR)** is the sum of corrective maintenance time divided by the total number of failures during a given time interval. In the case of a particle accelerator, this may, for example, include waiting for radiation decay.
- **Redundancy** is the existence of more than one means for accomplishing a given function. It can be:

- **Active**: if all redundant items operate simultaneously, or
- **Stand-by**: in the case where one or more redundant items are activated solely upon failure of the primary item performing the function.

Finally, a system can be classified as **non-repairable** (missile, etc) or **repairable** (particle accelerator, etc).

2 ACCELERATORS: RELIABILITY AND AVAILABILITY CONSIDERATIONS

Although frequent system failures may be an annoyance, if each failure can be repaired in a very short time so that the system has a high availability, and the maintenance costs are reasonable, then the poor reliability may be acceptable. For example, if failures occur on average every fifteen minutes but can be repaired in a few milliseconds the user will not be too concerned. On the other hand, if repair of a failure takes hours or days, the user has a non-available particle accelerator, which will have a significant effect on Machine Operation and … credibility!
We will see that this question is key issue for the design of the **High Power Proton Accelerator (HPPA)**, which will be used in the **Accelerator Driven System (ADS)**.
The operational effectiveness of a system is obviously influenced by the way its components were designed and built. It is, however, also influenced by the way these components are used and maintained.

2.1 Reliability and availability of particle accelerators: evolution of users requirements with time.

The 70’s was a transition period in the history of particle accelerator reliability. Of course, at that time, the technology and physics concepts of particle accelerators were well advanced: linear accelerators, cyclotrons, and synchrotrons could already be found in the four corners of the globe. But until then, the Users of these particle accelerators were generally also the designers! The main figures of merit were the energy and intensity. Users accepted long failures provided they could sometimes do experiments within the framework of these figures of merit.

In the early 1970's new high-intensity, intermediate-energy accelerators were built at laboratories in Switzerland (SIN), Los Alamos (LAMPF), and Canada (TRIUMF). These new ``meson factories" produced pions (and muons) of several orders of magnitude more than previous sources. It was the beginning of 'meson' factories and accelerator physicists were now supposed to serve a community of experimental physicists with machines as reliable and available as possible.

Also around that time, motivation was high for the design of dedicated storage rings for the production of synchrotron radiation. When the 5-GeV NINA electron synchrotron located at the SRS Daresbury Laboratory in the UK shut down, a plan was approved to build a 2-GeV electron storage ring at the same site expressly for synchrotron radiation. These new machines brought new constraints: large numbers of Users for short periods of time, short lifetime of biological samples, heat load on beam lines such that hours were necessary to recover from a micronic positioning of the monochromators after a beam interruption. Nowadays, an X-ray source can host about 60 different experiments at the same time! These machines therefore need a high level of availability and reliability. Typical figures for these machines are an availability of over 93 % and an MTBF in the range of 10-50 hours.

In parallel to these developments, medical applications took on a huge importance, whether this be for diagnosis or therapy. In these cases, the accelerator must be available when the patient is ready to be treated. More than 10 000 cancer patients have been treated at over 10 accelerator laboratories the last 40 years [2]. In addition, there may be budgetary consequences following Machine unavailability since a typical proton therapy centre employs about 120 people (doctor, physicists, etc), costs about 100 M€ [3] and can treat 3500 patients per year!

To conclude on the subject of existing systems demanding a very high level of confidence, I would like to refer to one exemplary industrial application:

- In recent years, Ion Beam Applications (IBA) has developed and installed 16 cyclotrons for the production of ^{103}Pd [4]. Given the 14 day lifetime of the ^{103}Pd, used for prostate cancer treatment, these cyclotrons have to run for continuous periods of one week and hence require a high level of availability. Although the dominant perturbations are very short RF sparks, the total downtime of these cyclotrons is less than 1 %!

3 STATUS OF SOME TYPICAL EXISTING FACILITIES

3.1 For neutron production

3.1.1 SINQ: a *continuous* spallation source.

The neutron source, SINQ, located in Switzerland, is fed by a high power cyclotron delivering 1.8 mA intensity protons of 590 MeV out of which 1.2 mA goes to SINQ target. The beam power available is roughly 1 MW and this is the reason why this cyclotron is considered to be the reference in its field [5]. Indeed the extrapolation to the multi-Megawatt system required for ADS is reasonable. Let us take a look at recent statistics [5].

Interruption time	1'-3'	3'-15	15'-60'	1-2h	2-6h	6-12h	12-24h	> 24 h
Number	5245	524	93	19	21	6	4	4
Time sum (hours)	92	42	42	25	75	45	70	167

Table 1: Beam interruption distribution > 1 minute at PSI in 2001

Interruptions of between one and three minutes represent 89 % of beam trips, i.e., 5245 failures. These beam trips are typically due to discharges in the electrostatic elements in the cyclotron. After such a trip, about 20 seconds are needed to ramp the intensity. This problem becomes particularly critical as the power increases (1.5 mA -> 1.8 mA). Only a few events are responsible for large downtime: missing redundancy of some cooling equipment, savings on power supply spare parts, 'run until it fails' policy for RF, etc. PSI experts agree that drastically reducing the downtime due to (long) failures is solely a financial issue. No technical obstacles have been identified and a program has now been set up to achieve these goals. However the reduction of short beam trips remains a real challenge! The behaviour of electrostatic elements is not well understood (this assessment is agreed by most RF experts in many accelerators centres!). PSI has developed a strategy to reduce this type of short beam trip [6]. Measures have been taken to increase the MTBF (RF voltage breakdown inducing beam trips) and reduce the MTTR. Since this could be considered as a point of general interest, I will go into more detail: In order to reduce component failures, a fault diagnosis tool was implemented, providing comprehensive data about RF transient events: main RF parameters are buffered and after a beam trip, the buffer continues to be fed for several hundred µs. Very detailed information in the µs range before and after the event can then be extracted. Modern quality control management was developed at all levels. In order to reduce the absolute number of beam trips, the RF cavities were thoroughly conditioned (thus avoiding breaking the RF windows), the beam is no longer turned off during self-recovering µ-sparks ≤ 200 µs, a ramping procedure was established in order to recover full resonator voltage within a few seconds and the beam after 20 seconds. To increase the lifetime of RF coupling windows, RF sparks are actively detected in order to shutdown the RF driver within a few µs, hence reducing the amount of evaporated metal, which is the main cause for cracks in the RF windows. Since then, the lifetime of

couplers at PSI has been dramatically increased. The remaining challenge is to reduce the number of µsparks and non-recovering sparks by understanding the cause and thoroughly studying the breakdown mechanisms. The fast event datalogging system has already been very helpful in this respect.
To reduce the downtime after a failure, the event datalogging system mentioned above is extensively used and in addition, a rigorous spare part policy has been implemented. Furthermore, equipments are designed to allow fast interchangeability of units/components. For subsystems with limited lifetime (e.g. klystrons), a policy of preventive maintenance is applied: this equipment is replaced after a predetermined operation time. Other parts (with an "undetermined" lifetime) are regularly inspected and each failure is now considered as an opportunity to improve the design.
After a few years of this strict but fruitful policy, the number of RF trips has been considerably decreased. At the end of 2001, not a single RF event greater than one minute was recorded over a 10-day period!
This first example demonstrates that, from a technological point of view, there are no insurmountable technological obstacles. It is, however, also a matter of finance, manpower and time!

3.1.2 LANSCE: a versatile proton source.

LANSCE is a spallation neutron source based on a Linac set-up [7]. The proton Linac can simultaneously accelerate H^+ (1.25 mA) and H^- ions (70 µA) to an energy of 800-MeV. The first stage of the accelerator contains injector systems for each kind of particle (H^+ and H^-). At the end of the Linac, a kicker sends H^+ into an area where the APT project (Acceleration Production of Tritium) conducts materials irradiation tests whilst H^- are sent to a proton storage ring which will convert 750 µs H^- macropulses into 0.25 µs, intense proton bursts that provide the capability for precise neutron time-of-flight measurements. A thorough failure analysis has been conducted for years at LANSCE. Excellent detailed information can be found in [7]. The average number of trips for H^+ is 1.62 trip/hour whilst this number is 0.78 for the H^- beam. Detailed statistics give no room for doubt; the H^+ injector is responsible for 90% of the trips whose duration is less than 1 minute and responsible for 77 % of all trips (3584 trips linked to the injector in 2870 hours). Next to the injector is the RF system, responsible for 5 % of all beam trips linked to the H^+ beam. However, H^+ injector downtime represents only 30 % of the total downtime. However, these impressive figures must not hide the fact that the general availability of the H^+ beam was 86 % in 1997. For the H^- beam, the injector looks somewhat more 'reliable' and represents 26 % of all trips. The reason is that this injector is more stable. However, it is essential to mention that both injectors are Cockroft-Walton type injector. Nowadays, microwave ion sources have proven to be much more reliable and suitable for future accelerator systems. Let us take the example of SILHI (a CEA ion source for the IPHI HPPA-project), which produced a 75 mA proton beam for a 104 hours-test with a single failure of 2.5 minutes only [8]!

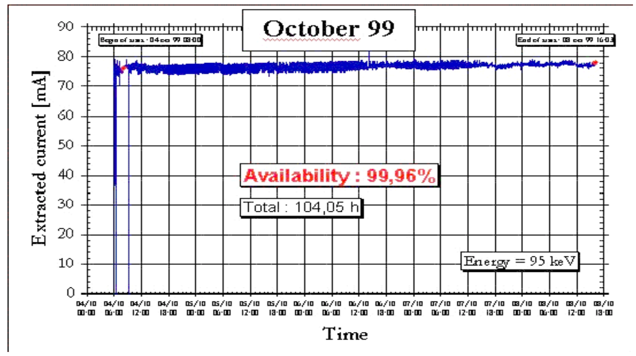

Figure 1: 104 hours-test with a single short failure on SILHI ion source.

As a first conclusion, failure databases of existing facilities must be 'decoded' carefully. They are clearly crucial in understanding weak points and are the fruit of experience. **However, data should not be blindly extrapolated for future accelerators since accelerator technology is in constant evolution**.

3.2 X-ray sources

3.2.1 General facts about X-ray sources reliability

X-ray sources are generally composed of an electron Linac followed by a synchrotron booster and a storage ring. Circulating electrons will generate intense X-rays, which will serve an extraordinary diversity of scientists. With present high-energy accelerators, about 60 experiments can be carried out at the same time around the storage ring. Should the accelerator stop for one hour, a whole community will be brought to a standstill for that time. Moreover, when the beam is back, it will take some time for the monochromators to retrieve their nominal micronic position (heating stroke effect). Finally, the demand for experiments is growing with time: the beam time demand is now about 2-3 times what can be offered! These accelerators must then be reliable, and available as much as possible. As an example of a high energy X-ray source (6 GeV) that has 10 years experience and which permanently tackles and improves reliability, the ESRF (Grenoble-France) will be reviewed.

3.2.2 The European Synchrotron Radiation Facility

The ESRF typically runs 5600 hours per year.

	1994	1996	1999	2000	2001	May 2002
Availability (%)	**91.4**	96.8	96.6	97.6	**98.2**	**99.4**
MTBF (hours)	**13.5**	41.2	31.9	38	**46.1**	**63**

Table 2: Evolution of accelerators availability and MTBF at ESRF

Availability has drastically improved with time, now reaching > 98 %, and the MTBF has almost quadrupled. The MTTR is about one hour. How could this be?

Since 1992, all failures are recorded in a database, in which the accelerators are classified into 40 sub-components. The main sources of long, as well as repetitive interruptions were quickly identified and solutions were brought. Here are some main examples aimed at improving Machine reliability.

The Grenoble area is prone to storms that can be particularly violent and frequent (on occasions, several times a day), provoking beam loss due to high voltage drops on the electrical mains. Statistics showed that this cause alone would prevent reaching a general availability of 95 %. The first action consisted in installing a wide infrastructure of 10 redundant 1-MVA diesel engines directly adapted to the 20 KV line and able to take over any mains drop [9]. In the case of the drop being less than 20% on a single phase, only the alternators are used to compensate (i.e., no diesel start, no use of accumulator, no disconnection from the electricity supplier). If a larger compensation is needed (drop > 20 %-160 ms or 50 %-60 ms), the diesel engines are started. Of course, the cost of this efficient installation was 6 M€ and the preventive maintenance costs represent 60 k€/year. After six years of experience, the benefits have been reaped: 150 drops/year are covered without diesel starts and 60 severe drops/year are compensated by diesel start- ups! Moreover, the electronic equipment is no longer subject to switching off abruptly, which was one of the causes for faster ageing.

At the same time, the RF system was responsible for many beam failures, which tended to be both long and repetitive. One cause, amongst others, for long RF failures were the klystrons, the worst case being the "death" of the klystron requiring about 8 hours to be replaced. To get around these problems, several actions were taken. A pair of cavities fed by one klystron was added in the storage ring. This released some power from the other klystron feeding the two remaining pairs of cavities. As a result, each klystron works well below their upper limit. In addition, after having improved the RF shieldings, klystrons crowbars (repetitive failure) have disappeared. A complex network of waveguides and switches has been installed in order to allow an extremely efficient redundancy: should a klystron fail, a spare klystron is ready to take over in ½ hour, wherever it is on the storage ring or on the booster. RF engineers have also laid to rest some generally accepted ideas: no correlation between klystron death and operation at full power can be made since only one klystron out of six died at full power. The klystron high voltage gun is the dominant problem: statistics made at LEP over 44 transmitters showed that 61% of the klystron failures were due to the gun!

Until the year 2000, radio-frequency arc detections were taken as a major contributor to MTBF limitation. In 2000, the Machine was stopped 38 times due to this kind of failure, representing a MTBF of 146 hours for this 'equipment'. A study of the triggered signals led to a preliminary redesign of RF arc detection electronics and following another retuning of the filtering time of these 50 detectors (in order to find a good compromise between real arc detections and wrong arc detections), the MTBF for this device is now reaching 404 hours for 2002! This is a good example of one low-cost efficient action!

Power supply failures can last a very long time when they occur (e.g., replacement of a transformer). To avoid a loss of time in these situations, a Super Spare Power Supply was built. Its role is to supply any magnet power supply that fails. Furthermore a matrix switching board was installed allowing any magnet family to be powered by the Super Spare Power Supply within less than one hour.

As a last example of preventive maintenance which is now applied and which undoubtedly prevents several tens of hours of beam stoppage per year, I should mention the radio-gammagraphies, which are systematically carried out after each vacuum intervention at the locations of the RF fingers in order to detect early problems in the mounting procedure. Since this procedure has been in place no more RF fingers have melted and we estimate that about 1 % per year of availability has been gained.

Analysing failure data and co-ordinating measures to fight them now represents a full-time job at ESRF, but the results are there!

4 FUTURE ACCELERATORS REQUIREMENTS

For many justified reasons not described in this paper, all ADS accelerator designers agree that a level of 10-20 long beam interruptions/year is an upper limit. 'Industrial' ADS accelerators should even aim at limiting themselves to 2-3 long trips/year. Trips < 100 ms could be accommodated thanks to fuel inertia [10] since the fuel temperature only drops after a few seconds. However, efforts must be made to get rid of the short trips that remain a concern for the spallation target window. There are two possibilities: one based on cyclotrons, the other based on linear accelerators. In latest developments, an RFQ design for the low energy part of the Linac (< 5 MeV) and supraconducting cavities for the high energy part (100 MeV – 1 GeV) are widely considered.

5 SUPRACONDUCTIVITY RELIABILITY *[11]*

5.1 General considerations

At a low working temperature, an impurity becomes a solid pellet, which can damage equipment; this is particularly the case for turbine wheels but also holds true many others components. A first step in equipment reliability is to have an irreproachable impurity measurement system. It is also essential to have a redundancy of major equipment (cold box, compressors, etc). This is the only way to provide continuous cooling capacity during shut down of some equipment for maintenance (or repair). This aspect must be considered during the design phase!

5.2 Cryoplant experience at different facilities

At KEK, 137000 hours of experience has been gained.169 failures have been observed out of which 114 were for the refrigerator system. After one year of 'childhood' disease, the reliability is now constant at 99.2 %!

At Fermilab, 76000 hours of experience allows to conclude that after upgrades and operator training, the reliability of this equipment stands at 99.5 %!

Finally, at CERN, 120000 hours have been accumulated by 4 cryoplants. The average reliability is 99.3%.

5.3 Conclusions

After an observed period of about 1 year necessary to modify weak points and train people, the average reliability of cryogenic facilities is higher than 99%.

6 A CHAIN IS AS STRONG AS ITS WEAKEST LINK!

Many R&D is done to improve reliability of accelerators: voltage breakdown mechanisms are thoroughly studied [12], RFQ designs are optimised [13], microwave ion sources can produce 100 hours of intense beam without a failure [8], ACTIVE redundancy schemes are proposed to compensate RF faults on high-power Linacs [14], etc. These efforts are useful only if all the links of the chain of reliability are considered. Failure diagnostics tools are essential and must be able to track and record any slow/fast event. These tools exist and are no longer a challenge. They must be part of a future design. Dedicated manpower must be considered to record and analyse failures and hence, detect weak points, initiate and follow improvement strategies. This is a dedicated job! Spare part policy must exist and must not be a day-to-day improvisation. Experts must be on standby and ready to intervene 24 hours a day (ESRF policy). Human mistake can be minimized with procedures and automation. This requires rigorous and well-trained operators! Thorough studies carried out in nuclear power plants show that human error probability for a repetitive task is about $3\ 10^{-3}$! Under high stress, this figure becomes 0.2 and shows the importance of well-trained staff! In the design phase, critical equipment must be identified and adequate active or passive redundancy must be foreseen at this stage, even if it is bought later for financial reasons.

Equipment must not work at full capacity; some margin must be allowed. With respect to this point, an excellent cost comparison between a normal and a conservative design for the European Spallation Source Linac has been made in [15] and shows that a highly reliable system would cost about 50 % more than a 'normal' design.

7 CONCLUSIONS

The author is firmly convinced that the "dream machine" of only a few trips per year is a possibility but this awareness must be present in the preliminary design phase. Budget is undoubtedly a key issue in achieving these goals (redundancy and qualified manpower is not free!). Should we go to extremes, we could consider an accelerator as a non-repairable system and apply failure-tree analysis, which is currently used for satellites and spacecraft [16]!

WEB possibilities must be exploited to bring together the experience of Institutes willing to share their reliability experience (database, dedicated papers, problems and solutions, etc). A WEB site dedicated to accelerator reliability aimed at sharing ideas and database elements will very soon start.

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