RELIABILITY AND MAINTENANCE ANALYSIS
OF THE CERN PS BOOSTER^{*)}

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1. Introduction and summary.
2. Operational record.
3. Initial design features
 - Favourable features
 - Unfavourable features
4. Maintenance.
5. Spare parts policy.
6. Operating temperature.
7. Effects of thunderstorms.
8. Fault diagnostics.
9. Role of operation staff and action by experts.
10. Conclusions and outlook
 - Acknowledgements
 - References
 - Figures

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CM-P00059558

*) A shortened version will be presented at the Chicago Particle Accelerator Conference (Poster Session).

1. INTRODUCTION AND SUMMARY

The PS Booster synchrotron (PSB) being a complex accelerator with four superposed rings and substantial additional equipment for beam splitting and recombination¹⁾, doubts had been expressed at the time of project authorization as to its likely operational reliability. In the event, for 1975 and 1976 the average down time (all four rings) was 1.5%.

The responsibility for the PSB is shared in the following way: PS/OP Group for operation, PS/ML Vacuum Section for vacuum, PS/CCI Group for computer controls, various PS Groups for some instrumentation, SB Division for building services, and PS/BR Group for operations support, maintenance and development of the accelerator. The credit for the above-average reliability is shared between those who built it and the hundred or so individuals running it (many of them working part-time on the PSB) who, whilst administratively in separate units, work effectively together.

The analysis presented includes the following items: operational record, design features, maintenance, spare part policy, operating temperature, effects of thunderstorms, fault diagnostics, role of operations staff and action by experts.

2. OPERATIONAL RECORD

The PSB operation statistics 1972 - 1976 were given recently²⁾. Here the record 1974 - 1976 is discussed³⁾ in terms of number of failures for 1000 working hours, MTBF (mean time between failures), and MTTR (mean time to repair).

With the low figure achieved for unscheduled beam-off time, all the systems are rather reliable, and breakdown of certain systems is as rare as once per run (of four to five weeks) or even several runs. Hence only overall statistics for the whole accelerator (including controls, vacuum and beam diagnostics) are presented.

Number of failures per thousand working hours

The equipment in operation during the years 1974 to 1976 was much the same, but the number of failures has been reduced by a factor two from 1974 to 1975 (Fig. 1). It would appear that the machine has essentially reached the middle (flat) part of the well-known failure rate ("bath tub") curve, i.e. the initial period was practically over at the end of 1974. (The high figure for run five of 1976 is due to the introduction of a new subsystem.) Other reasons for the increase in reliability are discussed in sections 6 and 7.

Mean time between failures stopping at least one ring

This diagram (Fig. 2) reflects the situation just described, in that the value of MTBF for the whole year increased substantially from 1974 to 1975 and slightly in 1976.

Mean time to repair

This time (Fig. 2) is the addition of the times needed to notice a failure, diagnose (see section 8) and repair it (possibly with the help of experts who however may need time to arrive on the spot - see section 9), and come back into operation. MTTR is thus largely a matter of good diagnostic tools, some provision of redundancy (see section 5), documentation, training, and availability of the staff involved. Almost all of these take time and progress was slower than for MTBF. However, if one disregards the breakdown of the two septum magnets during run six in 1976 (see section 4), the value of MTTR for the whole year came down from > 50 min. in 1974/75 to 25 min. in 1976.

3. INITIAL DESIGN FEATURES⁴⁾

Favourable features

Relatively low stress

The ring diameter of 50 m, and the peak energy of 800 MeV are fixed by external conditions, i.e. bunch to bucket transfer to the CPS, and increase of the CPS injection space charge limit by at least a factor seven. This made it possible to have good-sized straight sections whilst limiting the

peak bending field to 0,6 T. The C-shaped bending magnets adjacent to the injected and ejected beams have tapered coils, thereby allowing relatively small injection and ejection angles. Magnetic (rather than electrostatic) devices were specified for beam distribution to the four PSB levels, injection, ejection, and recombination. At 800 MeV they are powered continuously where possible. All this makes for comparatively low magnetic, electric, and thermal stresses. In five years none of the several hundred magnets (including kicker and septum magnets) failed due to electrical or mechanical breakdown, or overheating.

Radiation hardening and protection against stray protons

With a few and non-essential exceptions concerning special beam observation apparatus, no solid state electronics, or other radiation-sensitive components are located in the machine tunnel. The 0.4 mm thick vacuum chamber in the bending magnets is protected by fixed "scrapers" against stray protons and a heat-dissipating wedge protects each inflection septum. Efficient fast beam ejection is used exclusively. In five years no beam time was lost on account of the direct or indirect action by irradiation of the proton beam.

Others

Coverage by travelling cranes of sufficient capacity to move even the heaviest parts is provided for the injection line, the ring, and the transfer line. (Two pivot cranes were added later for dead corners).

Safety margins were applied as follows. Power supplies were designed for currents at least 10% higher than nominal; RF voltage generators, pulse forming networks for kicker magnets, storage condensers etc. were specified for voltages 10 to 20% above nominal; for thyristors of the main power supply a value of 2.5 was chosen for the ratio nominal inverse voltage/working inverse voltage.

Standardization was adopted not only with a view to saving cost for design and production but also for easier fault repair and maintenance. Built in test facilities and computer-assisted status analysis were planned in numerous cases from the start (see section 8).

Unfavourable features

Whilst beam can be delivered even with fewer than four rings working, the PSB design unavoidably has some inherent draw backs, as well as others resulting from features adopted for reasons of economy. These were however alleviated by particularly simple and reliable design (and persistent efforts to simplify even further and improve where necessary).

Complications

Beam splitting and recombination. The beam from the Linac is first split by a pulsed distributor followed by three septum magnets. It is then injected over a number of revolutions in the usual manner using (for each ring) a pulsed septum magnet and four slow kickers. After acceleration the beam is fast-ejected by a kicker and septum magnet and the beams from the four levels recombined by three septum magnets and three kickers. This adds up to fourteen septum magnets and a corresponding number of kickers (eleven fast and sixteen slow).

Independent beam control. In order to maintain high beam quality each ring has to have its own beam control system (phase lock, radial control, instability damping). At the end of the accelerating cycle, the four beams must be properly synchronized prior to ejection.

Independent magnetic corrections. Each ring has to have its own set of correction elements, dipoles, quadrupoles, sextupoles and octupoles; the number of independent controls is thus multiplied by about four compared to a conventional one-ring machine.

Space constraints

The vertical separation between rings was naturally kept to a minimum. This imposed severe constraints on the design of the RF cavity and associated final power amplifier. It also created some difficulties for the design of the kicker and septum magnets so that (also to save cost) the four injection and ejections magnets are designed as a unit, i.e. cannot be taken out individually.

Common vacuum system

For reasons of economy, there is a common vacuum system for the four rings. This decision has been amply justified by the record, but it does mean that in case of a leak, all four beams are stopped.

No local control room

The PSB is located about 300 m from its control centre, which is situated in the CPS Main Control Room (MCR). This obviously increases the time needed for local intervention by the MCR staff.

4. MAINTENANCE

Periodical overhaul and calibration

The following types of work

- i) Cleaning and reconditioning of electrical switch-gear, air filters, heat exchangers, water pumps and demineralisers, the air conditioning and drainage systems etc.,
- ii) tightening up of bus bar connections and similar work,
- iii) overhaul of cranes, lifts etc.,
- iv) checking of machine alignment and any realignment required,
- v) any other infrequent lengthy work.

are normally done during the annual shutdown (of about five weeks duration), and are carefully planned and coordinated.

Routine maintenance of electronics, including computers and vacuum systems etc. and recalibration (mainly of amplifier gains, zero offsets etc.) is often done during the two-day (or occasional ten-day) shutdowns between runs or even during operation, switching over temporarily to standby units where required.

Inspection and monitoring

PSB Staff have their offices and laboratories close to the machine equipment rooms, which facilitates frequent checking of operating conditions wherever this can be done without affecting the normal functioning of the accelerator. With solid state electronic equipment, the scope for surveillance by visual inspection is limited, but still useful.

Preventive replacements

Components with limited lives are kept under regular surveillance so far as practicable and replaced periodically, but expensive items (> several kFrs. e.g. thyratrons), are not normally changed unless they give positive signs of approaching the end of their lives.

Each ring has a single RF accelerating unit which is thus a particularly critical item. One of these is replaced by a rebuilt spare every year, each cavity is thus reconditioned every four years.

Removal and reconditioning is practically the only way of keeping a check on forms of deterioration that do not show up as a change of performance. An example of this type of problem occurred recently when after four years of fault-free service, two similar septum magnets failed within two days. The failure was found to be due to electrolytic corrosion of metal-ceramic joints, which could in principle have been detected earlier, though only at considerable cost.

Whilst this type of activity does absorb man-power, it has the great advantage of ensuring that the work can be scheduled normally and efficiently. (Ad-hoc repairs on the other hand are usually grossly inefficient: wasted travelling time, right man not always available, etc.).

Action after failures

Following a practice initiated earlier for the PS⁵⁾, failures, and particularly those causing a machine stop, are regularly discussed as described below (section 9).

The aim of the discussion is to establish

- i) what went wrong,
- ii) what was done to set it right,
- iii) what further action, if any is required,
- iv) whether there are any conclusions of general interest than can be drawn?

In this context the action sometimes means re-design (like mounting short-life components on modular plug-in units), or more preventive replacements, extra spare parts or even a fresh look at the spare parts policy.

5. SPARE PARTS POLICY

The PS policy as it evolved over the years^{6,7)} can be summarized as follows:

Because of limited resources a spare unit is only provided for any unit whose failure either

- i) stops the PS altogether or at least service to a major user (SPS, ISR, bubble chamber),
- ii) has a repair time longer than 24 h.

To implement this policy, (particularly for the more costly items (> 20 KFrS.), the following priorities were adopted:

- First priority : Units with intrinsically low or average reliability (example: septum magnets)
- Second priority : Units with high reliability but which would have a repair time of twenty days or longer (example: transformers), or particularly radio-active units (mainly second spare for septum magnets).

Within this general frame, the person in charge of a given equipment proposes the particular solution to be adopted. The decision will also depend on such considerations as importance and frequency of functioning, degree of stress, level of experience with this equipment, and man-power resources for interventions.

It is noted in passing that with the possible exception of items present in large numbers like small power supplies, theory⁸⁾ is of limited use, demonstrating mainly the interest of cold redundancy (= standby). This solution is being adopted for all power supplies, RF power amplifiers, the equipment in water cooling systems, and the control computers. Hot redundancy (= spare on line) is used in the vacuum system, i.e. excess vacuum pumping capacity - which at the same time provides a faster pump-down after exposure to atmosphere.

At least one spare coil and usually a complete spare magnet of each type was ordered already during construction, and similarly for other systems. A larger stock of spare components and units was built up over the years along the lines described, and is still being completed.

Spares are kept in working order (septum and kicker magnets under vacuum) and tested periodically.

6. OPERATING TEMPERATURE⁹⁾

Of the various causes for random failure of electronic equipment and the like, operating temperature appears to be the most critical. Figure 3 shows the typical Arrhenius relation between temperature and failure rate for a plastic encapsulated silicon transistor. Other types of components have either slightly lower or markedly higher acceleration factors, like two to three for a 10°C rise in the case of electrolytic condensers.

An example of this strong temperature-dependence can be found in the collective behaviour of the 25 high-power dc supplies all situated in the same equipment room. (10 KW - 300 KW, current regulated to 10^{-4}). Extra cooling was installed resulting in a drop of up to 10°C in cooling air temperature. This is considered by those responsible for the equipment to have been a major factor in the reduction of the failure rate from about three per run in 1975 to about one per run in 1976.

7. EFFECTS OF THUNDERSTORMS

The PSB is connected to the Geneva urban electricity network, consisting almost exclusively of underground cables, so that it is not much affected by surges of atmospheric origin. However some time was initially lost by having the relays in the emergency cut-out system fed directly from the ac mains, so that the briefest voltage dip resulted in all the main breakers dropping out. Changing them over to the 48 V battery system greatly improved the situation. A further substantial improvement resulted from connecting the control computer to a "no break" supply.

The PSB being built on a slope, it is now protected on the higher side by a drainage ditch, and raised thresholds of strategic doors, which it is hoped will prevent a repetition of the two occasions when during extremely heavy thunderstorms a few tons of watery mud found their way into the accelerator building by an astonishing variety of paths.

8. FAULT DIAGNOSTICS

Whilst most of the other points have found satisfactory long-term solutions, marked improvements could probably still be made in this area. Progress was relatively slow because of:

- i) the intrinsic difficulty for a new machine of knowing what to monitor locally and what to transmit to the Main Control Room (MCR),
- ii) rather restricted control computer capacity,
- iii) a not very strong motivation (in view of the low down time), and
- iv) a feeling that at the existing diagnostics level available effort was better spent on improving the equipment reliability.

Local diagnostics

In addition to the indications of magnet over-temperature, cooling-water flow, voltages and currents, presence of timing pulses etc. these include facilities to check the digital transmission of control and acquisition signals. This is done both via local simulators and a mobile computer console¹⁰⁾ which has essentially the same capability as the main computer-console¹¹⁾ in the MCR.

MCR diagnostics

The four hundred status bits are scanned once per PSB cycle and the (code) name of the first element "not ready" or "off" and the number of such elements are automatically displayed sequentially on its midi-console¹¹⁾ or, on request, simultaneously on the main console.

As not all parameters for proper functioning are acquired by computer, it happens not infrequently that the first indication of malfunctioning is given by the beam itself, via the beam observation equipment. Introduction of a coherent diagnostics and alarm system is one of the objectives of the

improvement programme for the controls of the CPS accelerator complex¹²⁾.

General statistical programs¹¹⁾ are designed to bring out irregular malfunctions, correlations with other parameters etc. A number of special hardware test programs call the computer for fault finding in a particular piece of equipment. Software test programs are also provided.

9. ROLE OF OPERATION STAFF AND ACTION BY EXPERTS

Respective roles

Whilst most systems were designed or eventually made proof against misuse, down-time due to human error of the operators did occur occasionally, particularly in the beginning. Similarly, push-button switching-over to a standby in case of equipment failure is what is being aimed at as a long term solution. In the mean time the MCR operators are the obvious persons to attempt to get the machine back into operation, assisted where necessary by more qualified staff on standby. Apart from the diagnostics already described, they are helped in this by modular equipment design with a spare module available close by, an appropriate documentation, and extensive training in the proper operation and the emergency repair of all PSB equipment. Exceptions are cases where

- i) these conditions are not (yet) fulfilled because of staff and budget restrictions,
- ii) safety rules forbid the operators to have access to the equipment,
- iii) this approach is impractical (e.g. replacement of a septum magnet).

The equipment specialists are in these cases called in, usually by telephone or the long-distance (30 km) paging system. It speaks for the dedication of the PS staff that these calls have practically always been successful though no systematic picket system is in force outside working hours. Nevertheless in the latter case between one half and one hour is usually lost before the expert arrives. However, in many cases he can avoid this delay (and extra loss of sleep) by directing operations successfully from home even without a computer terminal.

Means of communication

Good communications are obviously vital. In addition to telephone, intercom and public address systems, they are facilitated by a computer-driven display of beam and machine data as well as messages, located in the PSB equipment rooms and laboratory corridors and refreshed each machine pulse. The mobile computer control console¹⁰⁾ in the PSB building has already been referred to. In addition there are the log books in the Main Control Room and in the equipment rooms which experts and operators consult frequently to learn what happened during their absence.

Discussion meetings

Finally, failures are discussed at the end of every run, first between staff from the Operations and Booster Groups involved in operation¹⁴⁾, and then between the operation staff and all PSB staff concerned with maintenance and development³⁾. Numerous improvements of procedures and equipment have resulted from these discussions. To make them really fruitful, it is important that

- i) they do not become a form of inquisition, and
- ii) a reasonable balance is struck between a mere listing of events and the opposite extreme of lengthy discussions between experts which are of little interest to the majority of those present.

CONCLUSIONS AND OUTLOOK

Persistent efforts to achieve and maintain a high standard of equipment reliability is not only justified by the benefits of the accelerator users, but also by the higher productivity of the staff¹³⁾. Thanks to constant attention from the design stage and to close, well organized collaboration of all persons involved, the unscheduled beam off time of the PSB averaged over a year was reduced to 2,8% (at least one ring off), or 1,4% (all four rings off). Because of ageing and higher intensity (i.e. towards an average

of 10^{13} ppp from the present $4 \cdot 10^{12}$ ppp) increased efforts will presumably be required in the future to stay at this low level. For this we plan, as in the past¹⁵⁾ to work both on the MTBF, 28 hours at present, and on the MTTR, 47 (25) minutes at present, the latter, it is hoped, benefiting from the new control computer system¹²⁾.

ACKNOWLEDGEMENTS

It is a pleasure to thank G. Brianti and G.L. Munday, and the CERN management, for their understanding and support in the area of accelerator reliability and maintenance.

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FIG. 1. NUMBER OF FAILURES PER 1000 WORKING HOURS

FIG 2. MEAN TIME BETWEEN FAILURES AND MEAN TIME TO REPAIR (STOPPING AT LEAST ONE RING)

FIG. 3 : Typical relation between operating temperature and failure rate per 10⁶ working hours for a plastic encapsulated silicon transistor.

(Figure taken from the literature⁹).