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RELIABILITY AND MAINTENANCE ANALYSIS OF THE CERN PS BOOSTER

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Introduction and Summary

The PS Booster Synchrotron (PSB) being a complex accelerator with four superposed rings and substantial additional equipment for beam splitting and recombination$^{1)}$, doubts were expressed at the time of project authorization as to its likely operational reliability. For 1975 and 1976, the average down time was 3.2% (at least one ring off) or 1.5% (all four rings off). The items analysed are: operational record, design features, maintenance, spare parts policy, operating temperature, effects of thunderstorms, fault diagnostics, role of operations staff and action by experts.

Operational Record

After the PSB operation statistics 1972-76$^{2)}$, the record 1974-76$^{3)}$ is discussed here in terms of MTBF (mean time between failures), and MTTR (mean time to repair). As breakdown of certain systems is as rare as once per run (of four to five weeks) or even several runs, only over-all statistics for the whole accelerator (including controls and beam diagnostics) are presented.

Mean Time Between Failures Stopping at Least One Ring

The equipment in operation during the years 1974 to 1976 was much the same, but the value of MTBF for the whole year increased 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.

Mean Time to Repair

This time (Fig. 1) is the addition of the times needed to notice a failure, diagnose and repair it, and bring the PSB back into operation. MTTR is thus largely a matter of good diagnostic tools, some provision of redundancy, documentation, training, and availability of the staff involved. If one disregards the breakdown of the two septum magnets during run six in 1976, the value of MTTR for the whole year came down from > 50 min in 1974/75 to 25 min in 1976, despite the strongly reduced time available for maintenance.

Initial Design Features$^{4)}$

Favourable Features

Relatively Low Stress. Facilitated by the relatively large (externally imposed) machine diameter, the peak bending field could be limited to 0.6 T, and the injection and ejection angles to about 3°. Magnetic (rather than electrostatic) devices are used for beam steering throughout. 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 because of electrical or mechanical breakdown, or overheating.

Radiation Hardening and Protection Against Stray Protons. Essentially 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 against stray protons by fixed "scrapers", 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 by the proton beam.

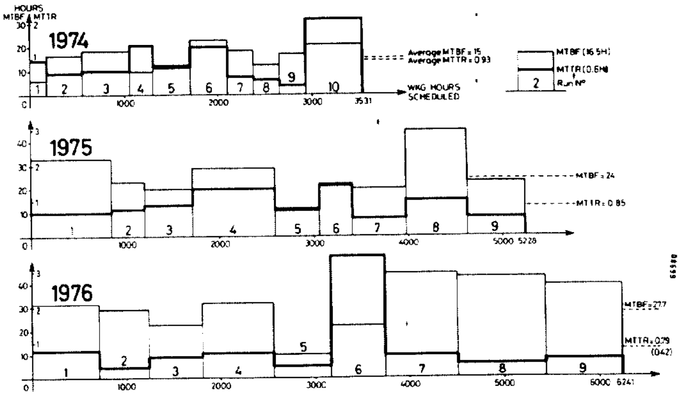

Fig. 1 MTBF and MTTR (stopping at least one ring)

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 condensors, 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 in design and production but also for easier fault repair and maintenance. Built-in test facilities and computer-assisted status analysis were often planned from the start.

Unfavourable Features

Whilst the beam can be delivered even with fewer than four rings working, the PSB design unavoidably has some inherent drawbacks, as well as others resulting from features adopted for reasons of economy.

Beam Splitting and Recombination. Beam distribution to the four rings, injection, ejection, and recombination require 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. Keeping the vertical separation between rings to a minimum 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 ejection 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 means that in case of a leak, all four beams are stopped.

Maintenance

Periodical Overhaul and Calibration

Any infrequent lengthy work is done during the annual shutdown (of about five weeks duration) and carefully planned and coordinated. Other maintenance (of electronics, computers, vacuum systems, etc.) is done during the two-day (or occasional ten-day) shutdowns between runs or even during operation.

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 kFr, 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. Recently two similar septum magnets failed within two days after four years of fault-free service. 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.

Action After Failures

Following a practice initiated earlier for the PS$^{5)}$, failures are regularly discussed 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 that can be drawn? Remedial 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.

Spare Parts Policy

Theory

With the possible exception of items present in large numbers like small power supplies, theory$^{6)}$ 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.

Implementation

The resulting PS policy as it evolved over the years$^{7,8)}$ can be summarized as follows: because of limited resources a spare unit is only provided for any unit whose failure either (i) stops the CPS complex (= Linac + PSB + 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 most costly items (> 20 kFr), 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 20 days or longer (example: transformers), or particularly radio-active units (mainly second spare for septum magnets).

At least one spare coil and usually a complete spare magnet of each type were 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.

Operating Temperature$^{9)}$

Of the various causes for random failure of electronic equipment and the like, operating temperature appears to be the most critical. An example of the strong temperature dependence can be found in the collective behaviour of the 25 high-power d.c. supplies all situated in the same equipment room (10-300 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 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.

Effects of Thunderstorms

Some time was initially lost by having the relays in the emergency cut-out system fed directly from the a.c. 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.

Fault Diagnostics

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 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 console$^{10)}$ which has essentially the same capability as the main computer console$^{11)}$.

Main Control Room 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-console$^{11)}$ 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 complex$^{12)}$.

General statistical programs[11] 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.

Role of Operations Staff and Action by Experts

Respective Roles

During working hours the repairs are usually done by the experts. At present, outside working hours, the MCR operators are the obvious persons to attempt to get the machine back into operation, assisted where necessary by more qualified operation staff on call. 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 duty schedule is in force. Nevertheless between one half and one hour is usually lost before the expert arrives from his home. However, in many cases he can avoid this delay by directing operations successfully from there over the telephone.

Means of Communication

In addition to telephone, intercom and public address systems, communications are facilitated by a computer-driven display of machine data and messages, located in the PSB equipment rooms and laboratory corridors, and refreshed each machine pulse. The mobile computer control console[10] in the PSB building has already been referred to. In addition there are the log books in the MCR and in the equipment rooms.

Discussion Meetings

Failures are discussed at the end of every run, first between staff from the Operations and Booster Groups involved in operation[13], and then between the operations staff and all PSB staff concerned with maintenance and development[3]. 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 to the accelerator users, but also by the higher productivity of the staff[14]. 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 4×10^{12} ppp), increased efforts will presumably be required in the future to stay at this low level. For this we plan, as in the past[15] to work both on the MTBF -- 28 h at present, and on the MTTR -- 47 (25) min at present. MTTR, it is hoped, will benefit from the new control computer system[12], keeping in mind however that the physical extension of the accelerator equipment rooms and the distance to the MCR alone set a natural lower limit.

Acknowledgements

The credit for the above-average reliability is shared between those who built the machine and the hundred or so individuals running it (many of them working part-time on the PSB). Whilst administratively in different units (various PS groups for operation, vacuum, computer controls, and some instrumentation, SB Division for building services, and PS/BR Group for operations support, maintenance and development), all these persons work effectively together. 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.

References*)

1. M. Innocenti, Documentation relating to the PS Booster (1966-76), CERN Int. Rep. PS/BR 76-13.
2. The PSB Staff (reported by K.H. Reich), The CERN PS Booster, a flexible and reliable injector, Proc. 5th All-Union Acc. Conf., Moscow, 1977, and CERN Int. Rep. PS/BR 76-14.
3. J.P. Delahaye, private communication.
4. The PSB Staff (reported by K.H. Reich), The CERN PS Booster, Design expectations confronted with reality, two years after start up, Proc. 9th Internat. Acc. Conf., Stanford, 1974, p. 480, and CERN Int. Rep. MPS/BR 74-10.
5. D. Dekkers, private communication.
6. See, e.g., B. Schorr, Introduction to reliability theory, CERN 74-16.
7. O. Barbalat, D. Bloess, J.H.B. Madsen and G. Nassibian, private communication.
8. J.H.B. Madsen, The maintenance at the PS, CERN Int. Rep. PS/DL 76-14.
9. See, e.g., G. Baribaud, La fiabilité en électronique: Revue générale et application aux alimentations, CERN Int. Rep. to appear.
10. G. Baribaud, The mobile control console in the Booster building, CERN Int. Rep. MPS/BR 74-17.
11. G. Baribaud et al., User's assessments of the computer controls system of the CERN PS Booster, Proc. 9th Internat. Acc. Conf., Stanford, 1974, p. 490, and CERN Int. Rep. MPS/BR 74-5.
12. B. Kuiper, private communication.
13. B. Frammery and A. Faugier, private communication.
14. K.H. Reich (Ed.), Maximizing productivity and employee morale in an era of tight budgets, Proc. 9th Internat. Acc. Conf., Stanford, 1974, p. 326.
15. C. Metzger, L'opération du PSB d'octobre 1971 à décembre 1974, CERN Int. Rep. MPS/Int BR 75-1.

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*) The full version of the present paper is available as CERN Int. Rep. PS/BR/77-1.