Chapter II.18

Life-cycle and operability of particle accelerators

Samuel Meyroneinc
Institut Curie, Orsay, France

Particle accelerators are used to generate particle beams for different kinds of use. Operability must be easy and simple for an industrial version with a high Technological Readiness Level (TRL), or complex and critical for large single accelerators designed for new research objectives. Our present text mainly focuses on this second type of specific machines and facilities. Beyond associated physics and technologies considerations, they are systems and facilities to be designed, constructed, and used for the expected purposes. The particle accelerators devoted to research have generally a long life ($>$ 20 years) and history shows that their lifecycles are unique, and generally neither smooth nor easy. Many good practices in project management and operation of particles accelerators can be found in the existing fields of building construction, or complex industrial systems (aeronautic, military) or other large scientific instruments (e.g. satellite). But they have their particularities: the specificities of the expected output (the particle beam, a complex multi-parametric physical object), the technologies (ion sources, RF, vacuum, etc.), the specific risks (direct or remnant radiations, electricity, etc.), the high expectation for performances or innovation, the usual associated international community. In the first section, we will describe the different classic stages of the lifecycle of a particle accelerator, in the second section we will focus on the operations stage with details on the reliability. In the third section, we will evoke some of the current trends: artificial intelligence, sustainability, and major cost of energy.

II.18.1 Lifecycle of the particle accelerators

II.18.1.1 Long lifecycle, retrospective or wished planning

A particle accelerator is built to last a minimum of ten years, some can have a lifespan of over forty years and upgrades are often carried out. From the very early times of discussions on the ideas and willingness to design and build a new accelerator, it can take several years to agree, find funding, design and build it, with many uncertainties on the exact schedule and budget. And once built, and operational for use, the specifics of the facility are deeply tied to that long prior history. Thus, when looking at the planning of the building of an accelerator, it will be important to differentiate the “retrospective” planning, drawn up after, when the accelerator is operational (see Fig. II.18.1 (left)) and the “desired” planning which are set and adjusted throughout its design and construction (see Fig. II.18.1 (right)). This also applies to operating costs.

II.18.1.2 The classic stages of the lifecycle

We propose here denominations for the classic stages of the lifecycle of a particle accelerator (see Fig. II.18.2 and Tab. II.18.1). These names can be slightly different depending on the conventions of

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- **2001**
- Australian Synchrotron Project funding announced by the Victorian Government
- **2002**
- Formation of scientific and machine advisory committees
  Site launch and preparation
- **2003**
- Machine design announced
  Building and associated facilities contract awarded
  Construction started
  Injection system contract awarded
- **2004**
- All particle accelerator systems contracts awarded
  Beamline design process starts
  Formation of industry advisory committee
- **2005**
- Building complete
  Machine assembly starts
- **2006**
- Installation and commissioning of machine and beamlines begins
  Selection of operator
- **2007**
- Commissioning of first beamlines complete
  31 July: Australian Synchrotron formal opening

ESS in Lund/Sweden

- Brightest neutron source worldwide
- 17 European member states
- First Neutrons: 2019
- Full power operation: 2025
- Decommissioning: 2065
- Investment: 1800 MEURO
- Sustainable energy concept
- 95% overall reliability

Fig. II.18.1: Left: example of retrospective planning (2013). Right: example of wished planning (2013).

each country or institution. It is better to have clearly and distinctly defined stages, rather than a continuous process without milestones, without beginnings and ends, which can create more misunderstanding between the different stakeholders.

Fig. II.18.2: Lifecycle with stages.

- **Desire-need:** it is a mix of "pull" processes, a scientific community needs a new kind of beam (with higher and/or different performances) and "push" processes (the accelerator community is able or has ideas for producing new kinds of beams). This stage can be very long, several years with an idea within a small group but without practical ideas to achieve it or without budget to go further. This stage of expression of interests may include a short feasibility process: it may concern the addressed theory of physics, simulation of the beam expected or the new technologies expected.
- **Preliminary design:** this step is the official step to further study what could be a global accelerator, and associated facility, capable of meeting defined global needs. All parts of the systems need to be studied and considered, but perhaps not with all clear details on performances and chosen technologies. It is now commonly accepted that this step must lead to the writing of a Conceptual Design Report (CDR), and the two expected results are: an overall dimensioning of each system and first rough estimate of the price of the facility. As this stage, showstoppers are identified

Table II.18.1: Denomination and typical duration of the stages.

Name of the stage	Typical duration (in years)	Associated names and considerations
Desire—need	10+	- Exploration - Expression of interest
Preliminary design	1–5+	- Feasibility - Conceptual design report (CDR) - Dimensioning and budget
Detailed design	1–4	- Technical design report (TDR) - All the data ready to build
Construction—installation	1–8	- Construction / Production - Building / Equipment - Laboratories / Industries - From design to real
Tests and commissioning	3 months–1 year	- Acceptance/Qualification - Preliminary tests
Operations Maintenance Upgrades	10–40+	- Operation - Maintenance (scheduled / unscheduled) - Updates/upgrades
Final shutdown—dismantling	1–10	- Lock-out, - Clean and clear, - Re-use?

as well as necessary Research & Development. This stage includes the risk management of the project and the evaluation “What I want, what I can achieve”. Detailed risk management is now mandatory for projects. The availability of skilled personnel must be taken into account.

- **Detailed design:** this step is generally initiated when the first financing for the facility has been accepted. And the outputs of this stage are clear: all the data required to build the accelerator, including a first official quotation of the facility (the building part) required for this. Here the Technical Design Report (TDR) must include all the data, dimensions, performances of the systems to be constructed, so a clear identification of work and budget needed (procurements, manpower and all the fees). It may happen that the TDR is not finished when funding is available, contingency must be considered. The cost of dismantling the facility should be estimated and technical solutions mitigating this cost must be considered.
- **Construction—installation:** this stage starts generally by doing the calls for bid for the building and the different equipment of the particle accelerator.
  - **The building** (infrastructure with walls and all the associated ancillaries) is of a paramount importance in a facility with a particle accelerator because it’s a first real concrete achievement to complete, it may represent 30% to 50% of the cost of the whole facility and many subjects are complex to install (cooling or cryogenics systems, IT networks and modules, safety systems, etc.). The key part of this stage will be the choice and the interfacing with the company in charge of the building work. The first usual critical path in the construction

phase is linked to the choice of thickness of the shielding walls (normal or dense concrete) which are defined by simulating the estimated radiation sources of the future machine. The building project must include considerations of the potential upgrades of the facility in the distant future (see Fig. II.18.3).

Fig. II.18.3: The building of the ESRF – Grenoble -France .

- **The construction of the equipment** concerns all the core parts of the accelerator (magnets, coils, RF, ions sources, vacuum chambers, etc.) but also the associated systems (power supplies, instrumentation, cooling systems, etc.). The procurement can be done from industry, with the appropriate tenders and contracts, or through collaboration agreements with external laboratories (case of an "in-kind" participation). In both cases, quality and detail of specifications, documentation, intermediate reviews and tests are key for success. In the case of project presenting a high level of innovation for specific systems, the process can also include beforehand a proof of principle (POP) or the construction of a prototype. Regardless of the process considered, a high level of quality assurance must be followed to manage the complexity of the particle accelerator's systems and interfaces.
- **The development of control systems and software** is a third and one of the most critical parts of a particle accelerator, from the layers very close to the hardware to the upper layers of monitoring and connection with the external networks and cloud. As for the equipment, the project management will have to choose the appropriate part of very structured method (e.g. verification and validation) and the part of agility (scrum and sprint). It will be pertinent to establish the minimum valuable project (MVP), i.e. the first working version ready as quickly as possible in order to avoid the fact that often the software is the latest system in particle accelerator project, although a minimum part is necessary to verify the first items of equipment delivered.

- **Tests and commissioning:** the process of development and construction of buildings and equipment includes a certain number of tests (unit tests, integration tests during interfacing, etc.). Thus, the final stage of tests is only considering those when the whole facility can operate. “Acceptance” tests can have significant importance in terms of contracts and relationships with payment deadlines. The end of the tests must correspond to the technical completion of the accelerator, which allows commissioning to begin, in the absence of major problems. The term “commissioning” is still a matter of debate for its meaning. We propose here: “the process by which the particle accelerator, after construction, is made operational and verified in accordance with design assumptions and performance criteria”. So, the main attention will focus on the beam, the main output and product given by the accelerator, so the measurement of its characteristics (values, stability, accuracy, reproducibility, etc.) and indirectly the diagnosis, the control and monitoring systems. The duration of the commissioning must be significant to include a long duration of use of the systems to examine thermal drifts and the reliability of all central and ancillary systems, an initial period of training and drafting of initial documentation to drive. A time buffer to correct large bugs observed or significant corrective modifications should be reserved. The management of this phase will be important to ensure safety on this new process, minimizing the stress to “finish the job” as well as the pressure and willingness of experimental users to start using the beam. An example of commissioning is given in Ref. [1].

- **operation—maintenance:** “operation” is what it is expected for an accelerator: the time to use it. This is detailed in Section II.18.2.
- **Final shutdown and dismantling:** the end of the life of a facility is always difficult to define. A scenario where the things are clearly decided beforehand is quite rare. In these cases, the particle accelerator is replaced by a new one at the same location, and a specific date is fixed for the duration (e.g. HERA accelerator at DESY, 1992–2007). The classic scenario is a slow decline in activity then the shutdown: no more interest, resources, or funding for use, or major failure with no possibility or resources to repair. Authorities and national safety laws will require a first official stop of the facility to ensure safety, to lock-out all the networks and close all the clearances to prevent accidents. Then secondly, a dismantling project must be carried out, in compliance with the requirements of the national and local authorities. The dismantling project is complex (dismantling techniques, regulations, number of other considerations) and with a significant budget and with a dedicated team. It will need to find several data of the used facility (e.g. hours and kinds of beam used) because the measurement and characterization of the radioactive activation of parts must be correlated to the simulations. The ultimate expectation from the authorities will be to leave nothing behind.

II.18.1.3 Classical issues associated with lifecycle

II.18.1.3.1 Customer-supplier relation and chain of values

Each stakeholder or teams are in charge of a specific system with a mixed knowledge of physics and technologies. Their respective deliverables contribute to the global equipment in association with the transversal issues (see Fig. II.18.4) . In terms of chain of values, the first supplier is the person/team in charge of a specific system and the civil society is the ultimate customer benefiting of the research works (see Fig. II.18.5).

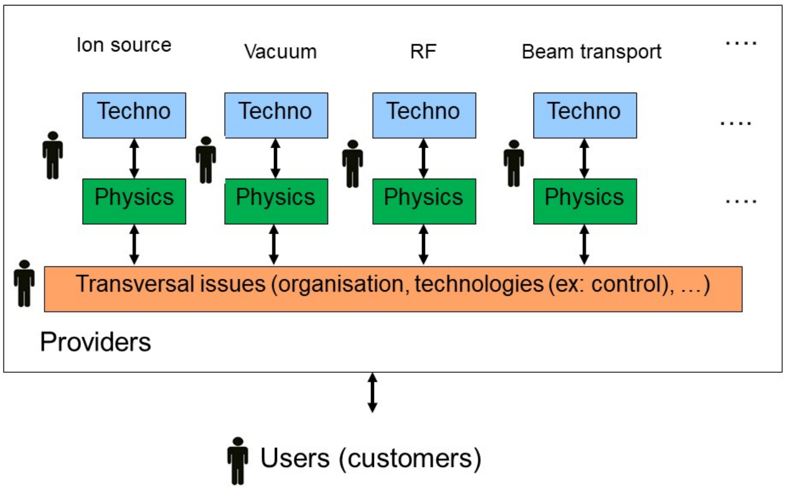


Fig. II.18.4: Customer/supplier relation within an accelerator facility.

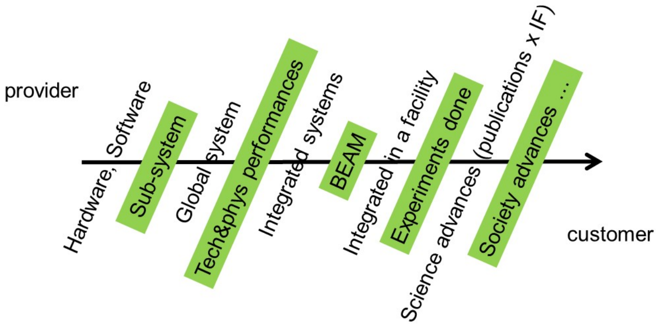


Fig. II.18.5: Chain of value from sub-systems to society advances.

II.18.1.3.2 Politics

As large-scale accelerators have a large budget (from 10 M€ to several hundred M€), part of the financing and monitoring decision process is linked to the political process (regional, national, European, international). It will consider the scientific arguments and benefits for society, and also the feedback for the region or country (employment, associated industries and potential innovations, reputation, etc.).

II.18.1.3.3 Funding and budget follow-up

The high cost and the level of risks of the accelerator projects (e.g. innovations, several uncertainties such as the duration for obtaining authorizations) underline the necessity of the permanent follow-up of the budget. There will be a distinction between the budget devoted to the construction of the facility and accelerator (also called CAPEX as CAPital EXpenditure) and the operating cost devoted to the operation and functional maintenance of the facility (also called OPEX as OPeration EXpenditure). Care should be taken with these budget estimates: in the past, projects have been canceled even after spending a significant part of the budget (Superconducting Super Collider (SSC) in Texas, United States, 1991–1993) and increased costs may impact funding of new projects. Any delay impacts the budget, meaning funding for construction staff increases. The particularity of international scientific projects is to have two kinds of financing contributions: IN-CASH (the country or laboratory gives an amount of money) or IN-KIND (the country or laboratory commits to provide a part of the machine, as magnets or ion sources, etc.). This second way is more interesting in terms of economic and learning returns for the contributor.

II.18.1.3.4 Risks and safeties, regulatory obligations

A particle accelerator is a place of many dangers for workers or visitors. Firstly, radiation, in a direct or residual way, that usually require and justify the presence of a radiation officer (and sometimes associated team) to ensure that the laws and recommendations are applied, and to help managers and staff under the principle of ALARA (As Low As ReasonAble). But there are many other risks: electricity (low and high voltage) sometimes with electromagnetic fields (permanent or waves), numerous gases (e.g. explosive), noises, hot components, chemical products, emergency exits to be provided, etc. The management of these risks requires to identify and minimize them during the entire lifecycle, to obtain authorizations from the appropriate offices, to train staff with regular awareness, to avoid accident which would be the worst situations (injuries to members of personal and shutdown of the facility during weeks or months).

II.18.2 Operability and reliability

II.18.2.1 The operations

The "operability" is the ability to keep an installation in a safe and reliable working condition. The "operations" of a particle accelerator are the processes to be able to deliver the required beam with the associated services. During the operations, the operators, usually from the control room (see Fig. II.18.6), check and adjust the parameters of the machine and in particular that the beams delivered are those

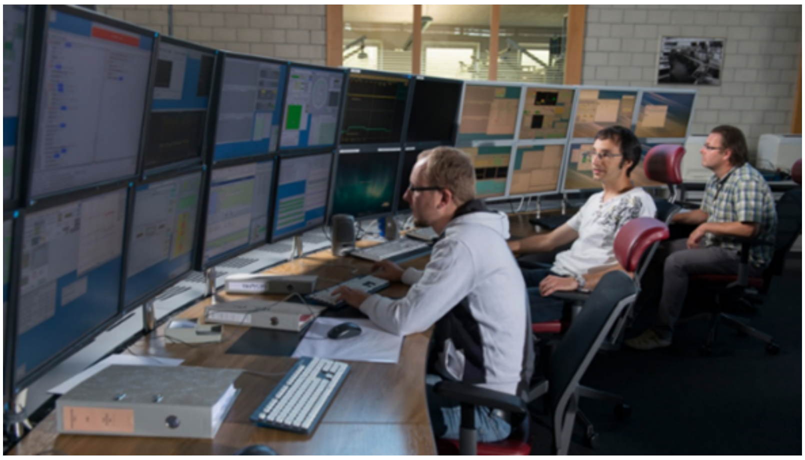


Fig. II.18.6: Operators in the PSI control room.

needed by the different users. This includes the monitoring and recording of parameters (automatic or manual, logbooks). There exists also a dedicated workshop, “Workshop on Accelerator Operations”, for which the most recent edition was organised in Tsukuba, Japan in September 2023 [2].

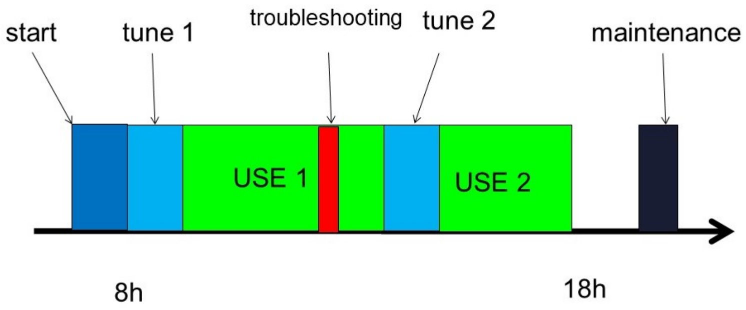


Fig. II.18.7: Example of a daily sequence of operations.

On a daily scale, there will typically be start-up and adjustment slots, slots to adjust other parameters and adjustments for different uses, unscheduled slots to resolve problems (troubleshooting) and slots for maintenance (see Fig. II.18.7). The operation also requires the proper management of the documentation (procedures, drawings, etc.) and the training of the operators.

II.18.2.2 The different kinds of maintenance

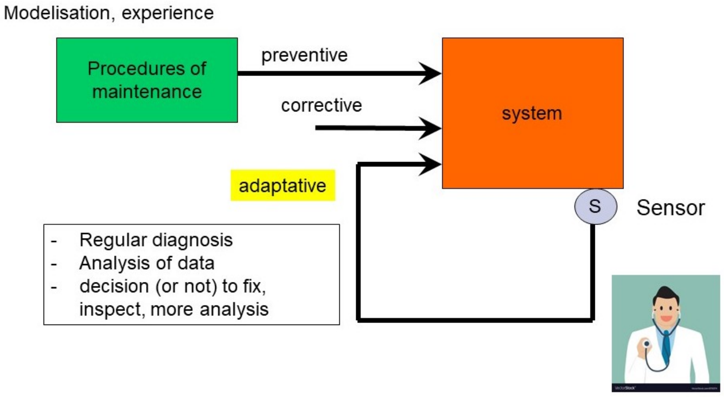


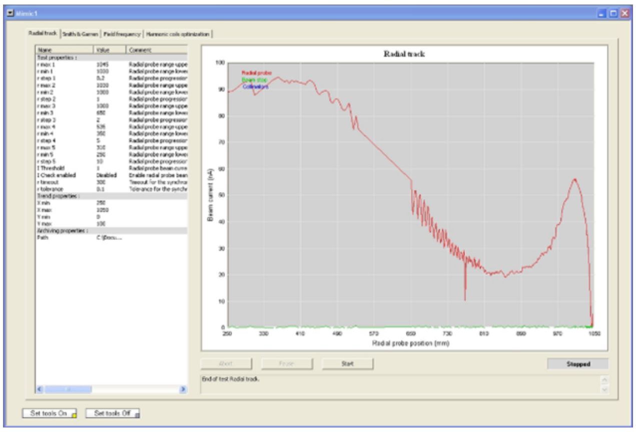
Fig. II.18.8: Principle of adaptive maintenance.

There are three kinds of maintenance:

- Preventive maintenance is a regular tasks to be performed on the systems, based on previous experience and recommendation of the supplier (inspect, clean, check, lubricate, calibrate, read, replace, test, etc.)(see Fig. II.18.9).
- Corrective maintenance is the troubleshooting of an unexpected problem which suddenly occurs. It is managed in several steps: awareness of problem(s), diagnosis, fix-replace, test. Corrective

maintenance is the worst situation because it affects the operations and requires several human resources with an unplanned schedule.

- Adaptive maintenance, probably the most suitable for particle accelerators, consists of regular diagnosis of the signal and data and the decision to anticipate a repair or change (see Fig. II.18.8).



End of test Radial track.

Fig. II.18.9: Example of a preventive maintenance - the radial track of the cyclotron C230 -IBA.

II.18.2.3 Yearly planning of the activities

On a yearly scale, a schedule is generally discussed and set with other kinds of slots such as long shutdowns for heavy maintenance sometimes including upgrades, slots devoted to R&D for the machine (see Fig. II.18.10).

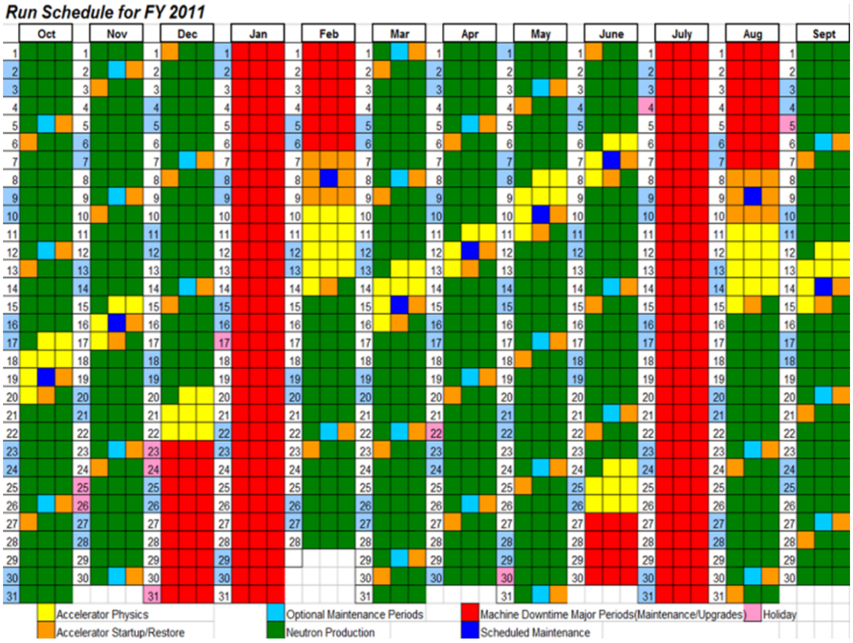


Fig. II.18.10: Example of yearly planning for a neutron facility.

II.18.2.4 Reliability

II.18.2.4.1 Importance and criticality of the reliability for particle accelerator

History shows that it's difficult to have regular operations on particle accelerators for many reasons: it is a combination of critical and sensitive technologies (radio-frequency, vacuum, electronics, cryogenics, software, etc.), with a lot of risks and associated regulations. It is a place involving high power, high loads, high voltage, high pressure, etc., and with permanent wear. There are usually sessions of production and sessions of development of the systems that oblige to switch between different modes. According to the costs for project and operations, the ability to use it for the expected needs is high. So, it is necessary to consider the reliability concept and ways to maximize it. There is a dedicated workshop, "Accelerator Reliability Workshop", for which the most recent edition was organised in Helsingborg, Sweden in June 2024 [3].

There are also some accelerators where the constraints of reliability are intense: in a synchrotron light source (see Fig. II.18.11) the number of parallel users is usually high (> 20), in a therapy facility the beam must be available all the weeks of the year. Non availability can have important consequences.

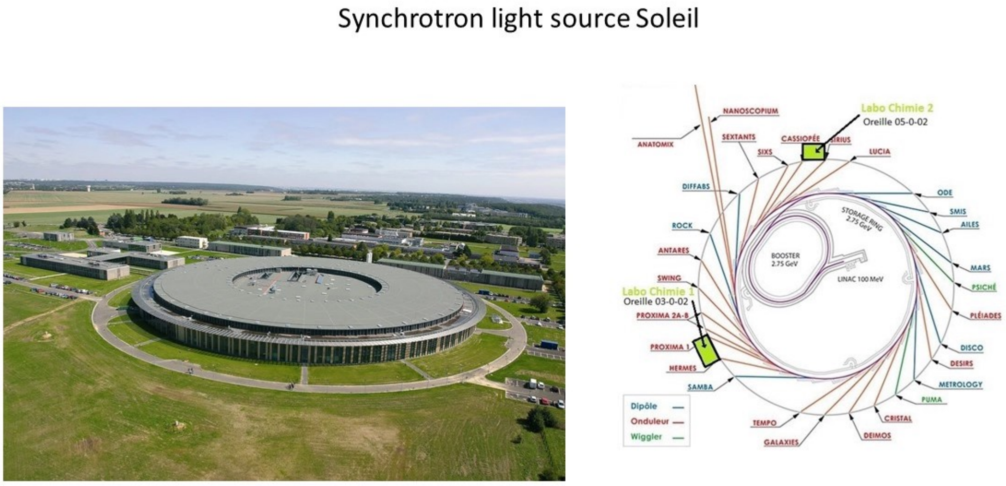


Fig. II.18.11: Picture and schematic drawing of the Soleil light source with its 27 beam lines for users.

II.18.2.4.2 Definitions about reliability

Reliability is the ability of a system or component to perform the required functions under stated conditions for a specified period of time. One also speaks of the **Mean Time Between Failures** (MTBF) and of the **Mean Time To Repair** (MTTR). The availability of a system (see Fig. II.18.12) is the ratio of the time when the system is operational by the time it was supposed to be operational (definition given in this lecture).

$$\text{Availability} = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})} \tag{II.18.1}$$

Beyond this definition, the discussion on definition of availability is a real opportunity of exchange between providers of the beam and users, and share their respective constraints and opportunities [4]. Another basic on reliability is the bath curve (see Fig. II.18.13).

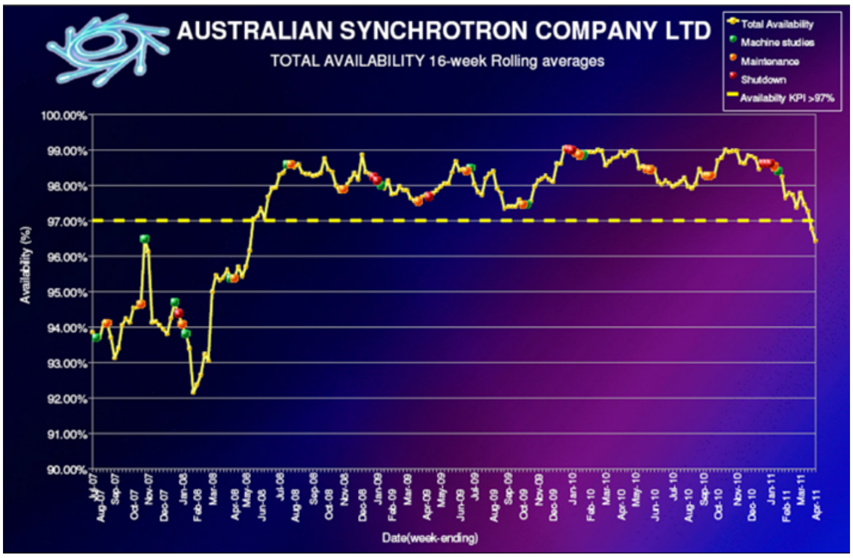


Fig. II.18.12: Example of figure on global availability of the Australian synchrotron.

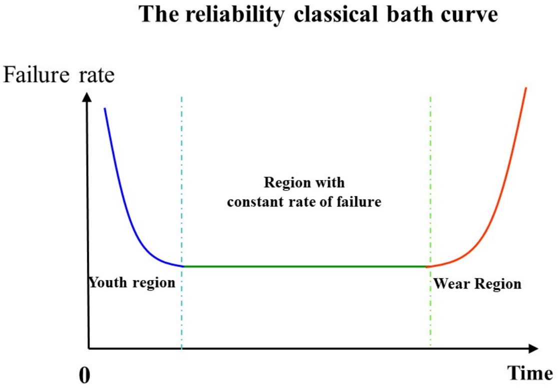


Fig. II.18.13: The classic bath curve during the lifecycle of a system.

II.18.2.4.3 Exercise

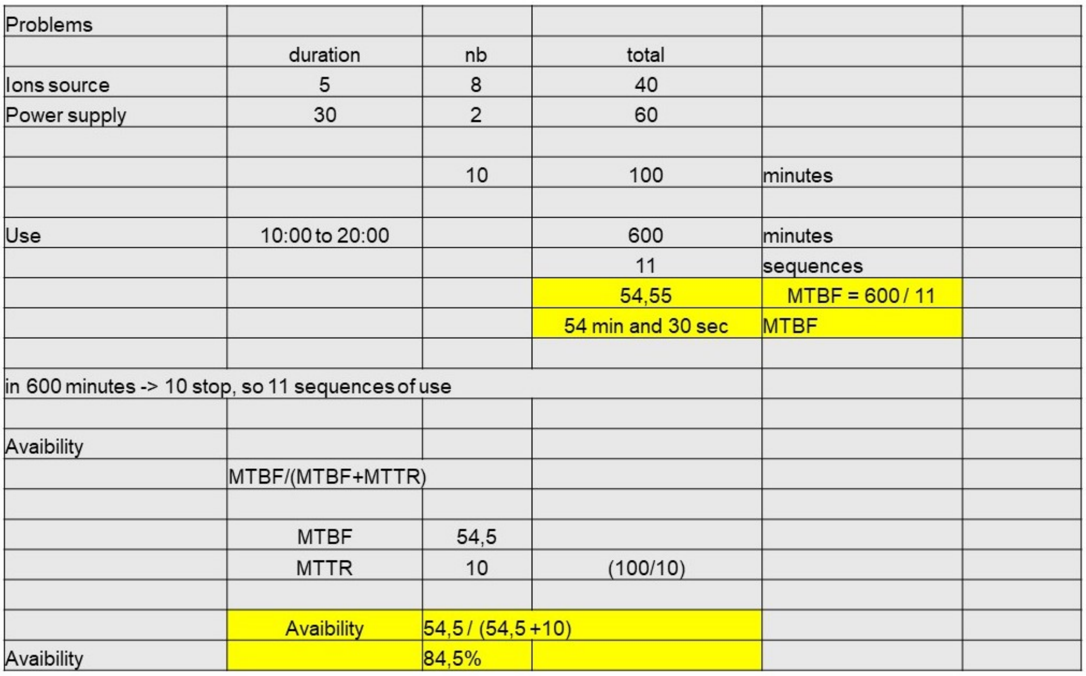
Questions:

An accelerator is used from 10:00 to 20:00. During this period, there were:

- 8 small failures of ion sources lasting 5 min each,
- 2 times (at 15h and at 19h) a failure of a magnet power supply, requiring 30 min to retune the beam.

1. What is the global MTBF?
2. What is the global MTTR?
3. What is the problem to solve first to do the best “physics”?

Answers: see Fig. II.18.14



Problems					
	duration	nb	total		
Ions source	5	8	40		
Power supply	30	2	60		
		10	100	minutes	
Use	10:00 to 20:00		600	minutes	
			11	sequences	
			54,55	MTBF = 600 / 11	
			54 min and 30 sec	MTBF	
in 600 minutes -> 10 stop, so 11 sequences of use					
Avaibility					
	MTBF/(MTBF+MTTR)				
	MTBF	54,5			
	MTTR	10	(100/10)		
	Avaibility	54,5 / (54,5 +10)			
Avaibility		84,5%			

Fig. II.18.14: Table showing calculation of the exercise questions.

And on *"What is the problem to solve first to do the best "physics"?"*, it depends on the experimentation, so it has to be discussed and agreed with the users.

II.18.2.4.4 Factors decreasing or increasing the reliability

Among the parameters **decreasing** the reliability:

- technological innovations,
- unique experience,
- number of specific interfaces,
- pressure on quality, budget, delay,
- etc.

Among the principles **increasing** the reliability:

- first tests done on a prototype with conditions as close as possible to the real ones,
- redundancy (see example on Fig. II.18.15), however careful evaluation is necessary, redundancy means more systems,
- over engineering (the design is done for performances higher than the expected or with more sophisticated technical solutions),
- maintainability, accessibility,

- large storage of critical spare parts,
- good management of the stages before operation: good understanding of the needs and of the users, good design and construction, exhaustive tests and debugs, complete commissioning,
- etc.

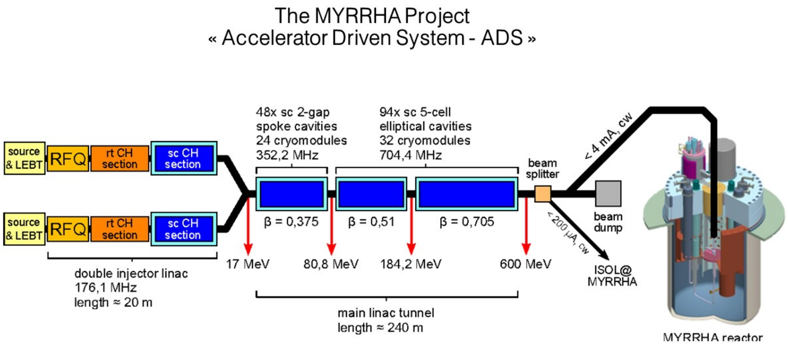


Fig. II.18.15: Example of redundancy: two injectors for the Myrrha accelerator.

II.18.2.4.5 Safety vs. (or with) reliability

There are two kinds of safety considerations:

1. Safety to protect humans (against radiations, fire, electricity, chemicals, etc.), absolutely mandatory, authorization to operate will not be given if this is underestimated;
2. Safety to protect systems (against mechanical damage, electrical breaks, quenches, contaminations, etc.) in most of the cases managed by a specific system (example of protection system for LHC at Fig. II.18.16).

In both cases, safety management will sometimes, at a first look, affect the availability of the machine (e.g. with regular trips of the beam in case of a parasite noise on a safety sensor, time to re-test the safeties after a repair). This first *"safety versus availability"* approach is in fact a wrong one, because in case of accident (for human or with a major damage to the system) the consequences would be catastrophic for the availability of the facility (long-shutdown to understand and fix the reasons and consequences of the accident). Therefore the good approach is to have *"safety AND availability"*, which requires a development of a good knowledge of the accelerator and its behavior.

II.18.3 Recent trends

II.18.3.1 Use of artificial intelligence (AI)

The design, operation and maintenance of particle accelerators have always use automation, feedback, computation, and control systems. However, the emergent significant AI tools open a new era of use of

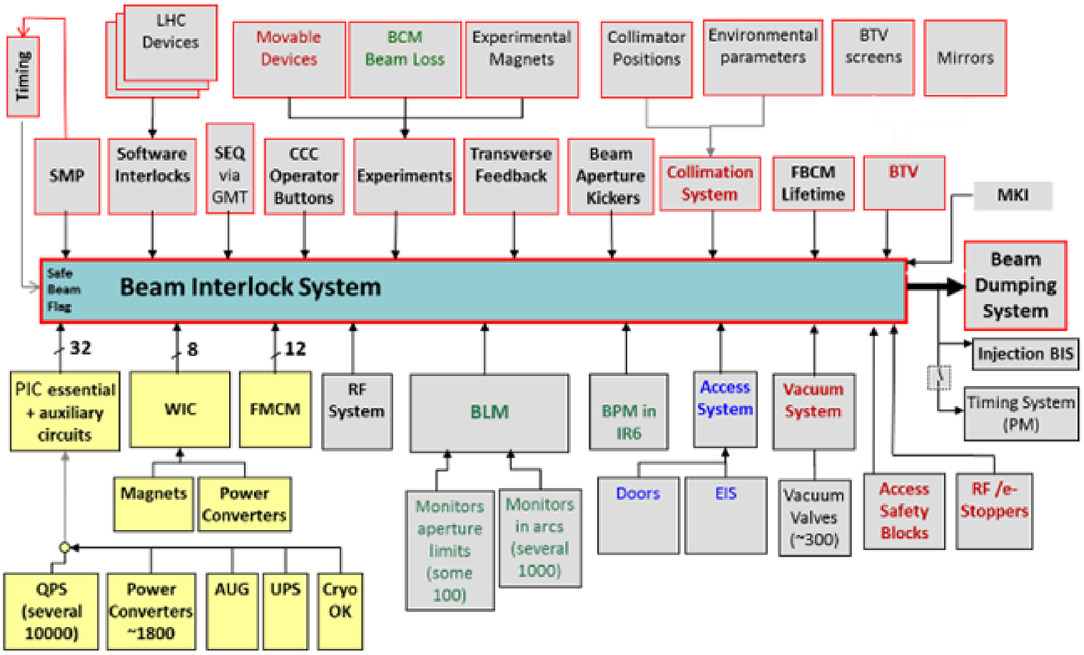


Fig. II.18.16: Machine protection layout for LHC (CERN).

“semi-intelligent” software, in particular to operate (e.g. tofind the appropriate set of parameters to tune a beam) or to maintain (e.g. to sort the big amount diagnosis data to find the pertinent ones to detect a drift or potential coming failure). But the use of AI must be introduced after an assessment of the human and machine resources which will be required and the capability to maintain and transmit the know-how of this “patch” during the whole lifecycle of the facility [5].

II.18.3.2 Sustainability

During the last thirty years, there were significant improvements in the behaviors and regulations to consider and decrease the environmental impact of large facilities, like the obligation to study and prepare the dismantling operation since the beginning of the lifecycle.

Because of the present first alarming signals of global warming and the collective expectations on sustainability (see Fig. II.18.17), the coming era will require an increased attention in many fields: minimize the pollutions and emissions, minimize the consumption of energy, water, etc., minimize the waste, maximize the recycling, maximize the lifetime. And this by direct or indirect ways (e.g. process for building, travel for meetings, etc.).

This turn has been started in the community of particle accelerators where these impacts are significant. The reference for this will be standards like ISO 50001 (Energy management systems – Requirements) or more specifically the ISO 20121 (Event sustainability management systems). There are also dedicated workshops like “Energy for Sustainable Science at Research Infrastructures”, for which the most recent edition was organised in Grenoble, France [6].

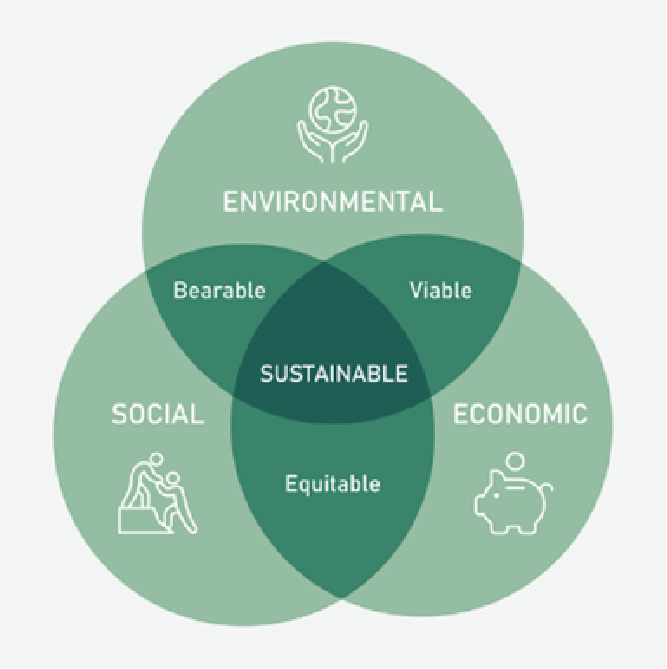


Fig. II.18.17: Issues associated with sustainability.

II.18.3.3 Major increase of the energy cost

The last ultimate factor of crisis, already included in this sustainability panorama, is the cost of the electricity, vector of energy massively used by particle accelerators. The war in Ukraine started in 2022 caused a general increase of energy cost, which directly affected the facilities with accelerators with a large impact on operating costs (+150–300% for the bill of electricity). The paths explored and started are the following:

1. short-term: increase the energy budget and decrease others, optimize the use, monitor the waste, decrease the time of use;
2. medium term: change the process (e.g. transition to superconductor magnets, use of permanent magnets), optimize the connection and use of the electricity grid, recycle the heat produced;
3. long-term: new data to consider in the business plan for further facilities, choose technologies with reasonable use of energy.

II.18.4 Conclusion

Large facilities with particles accelerators for research purposes have long lifecycle. Because they are complex and sensitive systems with a part of innovations and R&D, the management of their project studies and construction must be carefully driven, by using experience and methods already known in building construction and industries. Then, appropriate methods must be used for operations to obtain safe and efficient use. The collective enthusiasm for sciences and the international diversity of skills (see Fig. II.18.18) are often the key factors to lead to success each of these stories.

The last societal requirements for higher sustainability and the increasing cost of energy represent new challenges for these major scientific tools. These places of excellence and creativity must now find solutions with appropriate technologies and reasonable science goals to pursue their high contribution to the society.

Fig. II.18.18: A team of a particle accelerator facility (GSI-Germany).

References

[1] H. Hotchi *et al.*, Beam commissioning of the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex, *Phys. Rev. ST Accel. Beams* **12** (2009) 040402, doi:10.1103/PhysRevSTAB.12.040402.

[2] 13th Workshop on Accelerator Operations, WAO 23, Tsukuba, Japan, 10–15 Sep. 2023, https://wao2023.kek.jp/index.htm.

[3] Accelerator Reliability Workshop 2024, Helsingborg, Sweden, 23–28 Jun. 2024, https://arw2024.com/.

[4] A. Lüdeke *et al.*, A common operation metrics for third generation light sources, Proc. IPAC2014, Dresden, Germany, June 15–20, 2014, pp. 56–58, 10.18429/JACoW-IPAC2014-MOOCB02.

[5] ICFAO: Workshop on Artificial Intelligence for Particle Accelerators 4th ICFA Beam Dynamics Mini-Workshop on Machine Learning Applications for Particle Accelerators (5-March 8, 2024) in Gyeongju, South Korea, https://www.indico.kr/event/47/.

[6] 6th Workshop on Energy for Sustainable Science at Research Infrastructures, Grenoble, France, 29–30 Sep. 2022, https://indico.esrf.fr/event/2/.