COMMISSIONING OF AN ACCELERATOR: TOOLS AND MANAGEMENT

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Abstract

Throughout the life of an accelerator project, the commissioning is a very important and exciting phase. It is preceded by a long period of design, calculations, magnetic measurements, installation, and alignment. We want the commissioning stage to be successful and fast; that is, attaining rapidly the set goals and making the machine available for impatient users. This paper gathers the experience of several commissioning phases for different types of accelerators such as SNS, JPARC, and LHC, as well as synchrotron light sources such as DIAMOND, SOLEIL, SSRF, and LCLS. The importance of preparation for commissioning on both technical and personnel levels will be covered. I will also talk about the concept of stages, anticipation of problems, and early involvement of many specialists in addition to accelerator physicists and future accelerator operators. Furthermore, I will outline the importance of having a control system that is practical, fast, and has the capacity to offer high level automated applications. Finally, I will highlight the indispensable role of diagnostics for the first injection and first turns of the beam.

INTRODUCTION

The commissioning is the ensemble of all the necessary actions for checking and tuning an accelerator in order to meet its specifications. It occurs after years of optics calculations and design works, equipment specifications, construction and tests, assembly, installation and alignment. It is clear that the pressure will be on the commissioning team to reach the goal as fast as possible. At the same time, it is critical that adequate time is taken to establish a sound understanding of the accelerator functions and to properly commission the instrumentation and the safety systems. For a smooth and efficient commissioning, an important effort must go into the definition of the objectives and the organization of the coordination as well as into the preparation of the tools to record and analyze the results. In this paper, I will relate my own experience of the commissioning of SOLEIL [1] as well as information collected from other accelerators recently or being commissioned, DIAMOND [2], JPARC [3], LCLS [4], LHC [5], SNS [6], and SSRF [7].

COMMISSIONING STRATEGY

Some commissioning considerations are specific to different types of accelerator but in general the standard approach encloses five steps: pre-beam preparation and tests, getting the first beam, beam-based hardware and software checkout, optics studies, high current intensity effects. In practice, these steps are not completely separated from each other, and there is not a well precise defined time to declare the commissioning over. However, this categorization can be helpful in setting priorities and thus providing a logical framework of actions. The average time required for a commissioning depends on the type of the accelerator and the adopted strategy. For the synchrotron light sources storage rings, the commissioning could take up to six months of non stop runs with some shutdown periods for maintenance and completion of equipment installation. A good plan is required to determine the number of necessary shifts to reach the objectives, the time required for analysis and discussion of results, the periods of shutdown, and last but not least the state and availability of team members who throughout the commissioning period could work on a 3 shifts of 8 hour basis, including week-ends. Some large accelerators are built sequentially and require several commissioning phases. The Linac Coherent Light Source (LCLS) is a SASE X-FEL project under construction at SLAC. The commissioning of the injector section was completed in August 2007. The second phase of the commissioning, including second bunch compressor and full Linac is planned for 2008, and the FEL commissioning is planned for 2009 [4]. The beam commissioning of the Spallation Neutron Source (SNS) was accomplished over 7 stages of 1 to 2 month duration, spread over 3.5 years [6]. This allowed early testing of software, hardware and integration issues on relatively short and elementary beamline sequences. It allowed also, system modifications or upgrades between commissioning stages. Nevertheless, this approach required early deployment of many systems, temporary utilities installation in early stages, and additional overhead for multiple starts.

PRE-BEAM PREPARATION

Organisation

A coordinator with a central team is generally in charge of leading the accelerator commissioning with beam. For round the clock operation (3 shifts of 8 hours per day) and more efficiency, the team is not restricted to accelerator physicists but has to include, since the early stages, representatives of the technical teams covering the main sub-systems like Linac, diagnostics, RF, magnets, power supplies, vacuum, control and safety. This allows for interdisciplinary exchanges to better identify and solve encountered problems and for efficient progress of the commissioning. The central team must also have considerable and effective support from many accelerator groups requiring on call duty for 24 hours a day. The commissioning program proposed by the coordinator and discussed with the central team should be flexible to allow for changes as a function of the daily progress and the availability of equipment and people. The commissioning plan is thoroughly developed to implement a well thought process in subsequent stages, as needed. The coordinator takes overall responsibility for implementing the commissioning program over a limited time period. This involves the writing of a detailed protocol for each shift, nominating the shift crews, ensuring a necessary overlap of a minimum of half an hour between two successive shift members, chairing weekly commissioning meetings, calling for meetings following each stucking point, and reporting progress and problems to a wider community.

The central team has to be trained before the beginning of the commissioning on the use of high level applications and operation, radiation safety, and security issues. Generally, the shift is driven by two members of the central team assisted by an operator.

Subsystems Commissioning

In most cases, the start up is a short time operation. One or few days might be enough to get the first beam around the machine. Nevertheless, there are examples of start-up that were plagued by different technical problems and required several weeks or months. This must be avoided at any price and that is why the hardware commissioning phase should not be skipped. A comprehensive and thorough hardware commissioning list is vital to smoothen the commissioning with beam. Of course, the list will depend on the type of accelerator. But, in general, one should check the following subsystems: survey/alignment, vacuum, cryogenics plant, timing system, controls, magnets, pulsed magnets, power supplies, RF system, diagnostics, machine protection, and personnel interlock systems. One must know in advance how the equipment should be checked, what parameters should be measured, and with what operational strategy. A long check list is developed for each accelerator subsystem and phase test. For example, the list should include polarity, motion control, location, power connections, etc. In some cases (such as LCLS, LHC and SOLEIL), there are also figures which graphically depict various magnet polarity conventions, BPM roll angles, wire-scanner orientations, etc. One should not have to do any profound thinking in the tunnel, and should simply refer to the figures. An example used at LCLS is given in figure1.

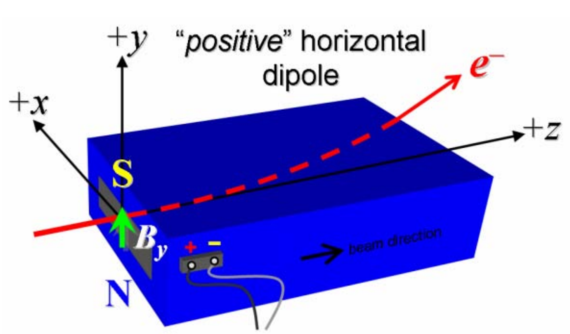

Figure 1: A "*positive*" horizontally bending dipole magnet) bends electrons in the +*x* direction.

These verifications require time and may appear tedious but it would be unacceptable to waste time during start up because they have not been done. Hopefully, the architecture of very large accelerators like LHC allows the commissioning of each of the eight sectors independently before the installation of the next sector.

The remote control of all equipment from the control room has to be available and tested before the start up, as well as the key commissioning tools and high level applications. This has a three-fold effect, minimizing the bugs, testing the equipment and probing the global control of the machine. A good communication between the central team, the control group, and the equipment specialists is then crucial to reduce debugging turn around time and to extend the information.

Most technical issues should have been sorted out during hardware commissioning. However, there will remain two main possibilities that could cause problems, which could only be revealed by the beam: aperture limitation and polarity errors not identified during the control.

Lattice Modelling

The machine requires a very accurate on-line optics modelling that shall be tested and ready for use in the control room before the start up. A complete and trustworthy (non-)linear model shall be composed with the databases of the measured magnets. The good quality of magnetic measurements is then a fundamental point. Special attention has to be paid to stability, precision and reproducibility in order to take into account the large number of magnets to be measured. As far as possible, defaults due to magnet construction errors have to be minimized. Great care has to be taken with quadrupole magnetic axis centring, which is a real asset for the commissioning and operation. Additional focusing effects coming from dipole magnet fringing field, gradient due to curved trajectory in dipole magnet, and difference between entrance and exit edges have to be taken into account. During the first days, the correction of the beam trajectory, the tunes adjustment, and the variation of the chromaticity will rely on the model response matrices. Having the most accurate model possible from the beginning facilitate the circulation of the first beam and provide an accurate and up-to-date snapshot of the machine to be made available as input into either off-line or on-line evaluation. On some specific case, an accurate optics model is essential for the protection of the accelerator equipment. The highly destructive power of the LHC beam, operating mainly in a superconducting environment, places stringent demands on the beam parameter control.

GETTING THE FIRST BEAM

The start up of an accelerator with beam is a unique exceptional, historical and highly emotional event. In this chapter, the example of SOLEIL will be taken to show the different steps of a commissioning with beam. It will be completed and illustrated by the experience of the other accelerators.

One should start by setting the Bending Magnet (BM) current. The quadrupoles, sextupoles, correctors and RF are off. Only the BM are powered to a field corresponding to the theoretical Storage Ring energy, taking into account the measured effective magnetic length. The beam is injected on the central orbit of the ring by an on-axis injection, so that induced coherent betatron oscillations are avoided. The trajectory of the beam in the Storage Ring is measured on several BPMs in a few cells downstream the injection point before the beam gets lost (no focusing). The minimization of the trajectory excursion in those BPMs corresponds to an energy deviation between the injected beam and the Storage Ring BM field. The correction can be applied either by modifying the Storage Ring BM field or by changing the extraction energy from the Booster. It is obvious that the highest is the number of the BPMs readings the best is the accuracy of this method.

The quadrupoles can then be powered; if there is no major problem and if the magnet alignment enables it, the beam can make several turns without any dipolar correction. This was the case on at least the last three recently commissioned synchrotron light sources (DIAMOND, SOLEIL and SSRF). Figure 2 gives the example of SSRF where up to 5 turns have been obtained with all correctors off. If the beam does not perform a complete turn, its trajectory has to be corrected step by step, in both horizontal and vertical planes, using the Storage Ring dipolar correctors and the BPMs in the first turn mode.

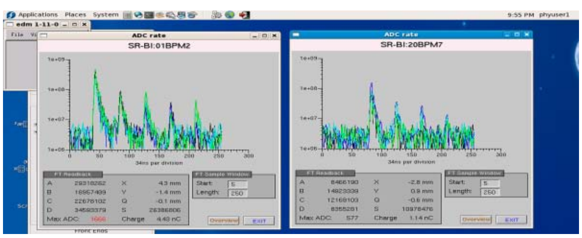

Figure 2: SSRF: 5 first turn in the Storage Ring.

With turn by turn BPMS, the analysis of the first turn trajectory can already provide some information like the integer parts of the tunes, the presence of potential obstacles, or wrong polarities. The first turn in DIAMOND Storage Ring revealed that the two last quadrupoles had inverted polarities. After modification, the beam performed 4 turns with correctors off. Figure 3 illustrates this effect where the beam intensity is shown in green.

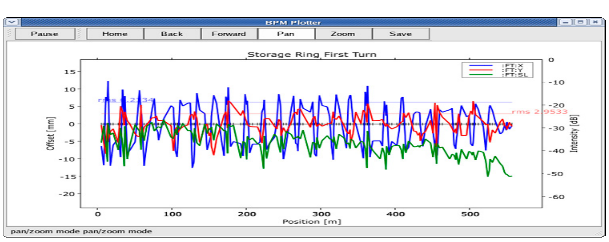

Figure 3: DIAMOND first turn revealed two quadrupoles with inverted polarities.

A rough estimation of the fractional part of the tunes and closed orbit can be obtained using the 4 turn algorithm. This technique may be very useful at this early stage of the commissioning. The precision of this measurement is expected to be 0.01.

The correction of the first turn enabled to improve the number of turns. The beam performed up to 50 turns just after this correction. This is shown in Figure 4.

The sextupoles can then be set at their theoretical values for zero chromaticies and ideally one can observe the transmission improving again and the number of turns increasing. Figure 5 illustrates the beneficial effect of the sextupoles at SOLEIL. With sextupoles on and RF off the limiting factor for beam survival is energy loss causing the beam to hit the inside of the vacuum vessel at a point of high dispersion.

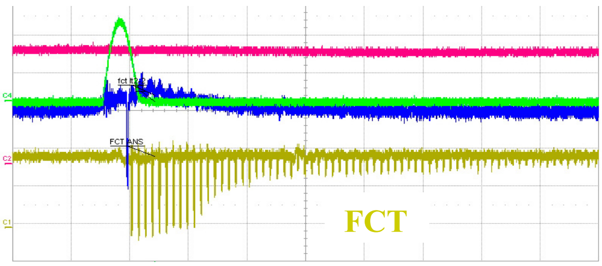

Figure 4: SOLEIL transmission improving after first turn correction. Turns read by a Fast Current Transformer.

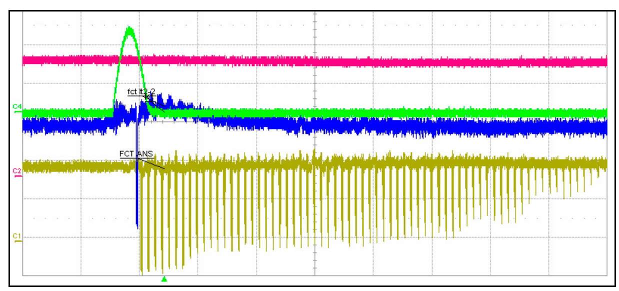

Figure 5: SOLEIL transmission and number of turns improving after powering the sextupoles.

At this stage, in collaboration with the radiation safety group, a first beam loss measurement and analysis can be made. Using one or combination of correctors, the beam can be lost at specific locations, so as to probe the tunnel shielding.

To get a stored beam, the RF cavity must be turned on and the RF frequency (phase) and voltage should be optimized for maximal beam survival. The potential problems might arise from a length error in Storage Ring circumference, timing error, or a mismatch between the Booster and the Storage Ring RF phases.

For the accumulation of the beam, the injection shall be switched to the normal off-axis injection. The RF parameters can be readjusted according to the criterion of optimizing the beam lifetime. Figure 6 shows the case of the first SSRF beam accumulation.

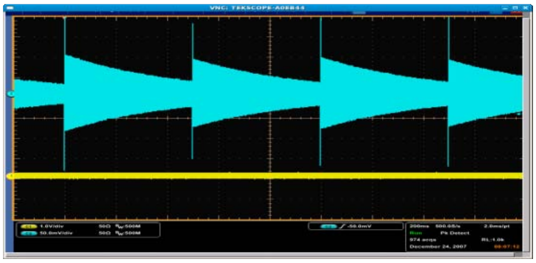

Figure 6: SSRF first accumulated beam.

Once these steps have been passed successfully, the enthusiasm is tremendous and one could savor the first synchrotron light from the visible synchrotron light monitor in the control room.
In general, the beam current is deliberately limited to a certain value until all machine protection interlocks had been fully tested.

LCLS injector first beam was quickly established to the nominal injector energy of 250 MeV and over only five months all injector systems were commissioned and the beam accelerated to as high as 16 GeV at the end of the SLAC. The SNS high energy superconducting proton linac, the accumulator ring and the transport line to the target commissioning has been also a great success.

BEAM-BASED HARDWARE AND SOFTWARE CHECKOUT

The beam-based measurement program comprises BPM offsets measurements, corrector polarities checking and calibrations, aperture scans, orbit interlocks, and machine protection validation. It includes also the optimizing and automating of the betatron tune measurements, and the calibration of the beam size instrument, like wire scanner or synchrotron radiation monitor.
It is also worth dedicated some time for tuning the acquisition system and calibrating with beam the Current monitors (Fast and DC Beam Current Transformers), and the thresholds of the Beam Loss Monitors. Before starting the first optics measurements, it is recommended to take the time to debug and optimize with beam the main high level control applications.

OPTICS STUDIES

In order to check and correct the optics of the machine, the following measurements have to be made:

- Beam Based Alignment
- Optimize RF frequency (circumference measurement)
- Response Matrices (orbit, tune, chromaticity)
- Beta functions at quadrupoles locations, and at BPMs
- Dispersion function
- Beam emittance and dimensions
- Betatron and synchrotron tunes
- Natural and corrected chromaticities
- Global and local coupling
- Momentum compaction factor
- Bunch length
- Energy spread
- Beam lifetime
- Momentum acceptance and dynamic aperture
- Effect of Insertion Devices
- …

A standard tool for restoring the linear optics in circular machines is the so called LOCO code (*Linear Optics from Closed Orbits)*, [8]. It is largely used all around the world. The sum of the squared differences between measured and calculated orbit response matrices is minimized in an iterative process. It is used to fit many parameters in an optics model, including quadrupole gradients, BPM and corrector calibrations. Constraints for large machines arise from the large number of BPMs and correctors, which requires large computer memory and CPU time. As an example, measuring a matrix response using 120 BPMs and 56 dipolar correctors in both planes takes typically 25 min at SOLEIL. A total of 896 parameters are used in the fitting procedure for the full coupled orbit response matrix. The use of LOCO at DIAMOND and SOLEIL enabled to restore the symmetry to ~ 0.3% RMS level in both planes. LOCO is also intensively used as a diagnostics tool. Indeed, the information gathered into an orbit response matrix is extremely valuable and can reveal quickly anomalies with equipment (BPMs, orbit correctors, coupling, focusing defects). As an example, when analysing the corrector tilts and efficiencies, LOCO gave hints about loose cable connections on a magnet [8].

HIGH INTENSITY

The beam current has to be increased at its highest value as soon as possible in order to speed the cleaning of the vacuum chamber by synchrotron radiation, to study the behaviour of the equipment as a function of high current intensity and of course to study the unavoidable instabilities due to collective effects. Third generation synchrotron light sources combine high current modes of operation both in terms of total and bunch intensity, along with small vertical vacuum chamber aperture adopted all around the machine to fit low insertion device gaps. This combination might result in severe transverse collective beam instabilities. Moreover, the electron beam can be driven strongly unstable by ions existing in the chamber.

ROLE OF THE DIAGNOSTICS

All the steps of the commissioning program rely on the availability of numerous diagnostics and their associated control system. It is certain that excellent beam diagnostics make beam commissioning much easier.
The turn–by-turn/first turn capability of the LIBERA BPM electronics [9] used at the last three commissioned 3rd synchrotron light sources (DIAMOND, SOLEIL and SSRF) was very valuable. This capability was successfully used for tuning the first turn, allowed to understand quickly that some magnets were having the

wrong polarity, and helped investigating the location of obstacles in the beam path. These BPM electronics can accommodate very low current on a single beam passage, which is what we really need in the beginning; it also provides, in the slow acquisition mode, a good accuracy and a very good resolution, which is necessary for the closed orbit correction and response matrices used in the optics studies. A flexible, stable, and reliable timing system is also of a great help since the progress of the commissioning depend on the radiation safety constraints and injector behaviour.

ROLE OF THE CONTROLS

A great part of the commissioning successes of the accelerators quoted in this paper are due to well developed, flexible, and robust control systems, which were available on day one. Many of the control systems are based on EPICS but the experience of SOLEIL, which uses TANGO as a full control system for the first time was very successful [10]. SNS developed a Java high level application framework (XAL) [11], which has been used also by J-PARC. Many facilities have benefited a lot from the Matlab Middle Layer applications [12], a set of functions designed to access the machine hardware, which mimic the more commonly used naming schemes in particle tracking codes and takes advantage of Matlab's matrix language. Graphical User Interfaces (GUIs) such as LOCO, plotfamily, orbit correction, and many others are included. Matlab based applications allowed to perform quick commissioning. Its script language and simple syntax, and mathematical and graphical libraries are major features that allow accelerator physicists to efficiently develop new tools with some autonomy with respect to the control group. Once an operational stage is reached, the limitations of the Matlab tools show up, and in order to provide upper level applications better matched to a robust routine operation they have to be slowly replaced with dedicated applications for almost all routine activities outside of accelerator physics work.

Electronic logbooks are nowadays very powerful and useful tools to collect share and find information on the start up, the commissioning development, the operation, maintenance, and failures.

TOP LESSONS

Some lessons learned from the commissioning experience of the accelerators cited above are summarized thereafter:

- Keep the commissioning simple and stage it.
- Wait for completion of installation and test of equipment before moving to commissioning.
- Make sure first order simple functions work first.
- Allocate some time in between beam commissioning shifts to analyze data and modify software or hardware.
- The availability of more than one central team member on shifts (in addition to the operator) is very useful. This helps in communicating knowledge, and combining people's skills and experiences to promote new ideas and approaches.
- A tool to easily save and restore machine settings is imperative.
- It is important to carefully document in the Electronic log book all failures of equipment and their causes, to help associated colleagues to better understand the problems and their remedies.

CONCLUSION

The most recent commissioning of accelerators have been performed in much shorter time than it used to be before. This is due to a careful preparation of the phase before the beam, a very detailed, extensive and accurate modelling associated with efficient analysis tools, a robust control system, and an excellent set of diagnostics ready on day one. Additionally, as it is expected in any projects, the tremendous enthusiasm enables to overcome rapidly most of the difficulties that may arise. The commissioning phase is a real team effort requiring great communications and very cooperative spirits.

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