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by

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ABSTRACT

The computer control system of the Intersecting Storage Rings (ISR) at CERN has always laid emphasis on two particular operational aspects, the first being the reproducibility of machine conditions and the second that of giving the operators the possibility to work in terms of machine parameters such as the tune. Already certain phases of the operation are optimized by the control system, whilst others are automated with a minimum of manual intervention. The paper describes this present control system with emphasis on the existing automated facilities and the features of the control system which make it possible. It then discusses the steps needed to completely automate the operational procedure of accelerators.

1. INTRODUCTION

The control of accelerators with computers is nowadays a well-established practice. As with most advances in the field of computing their introduction and acceptance as an essential part of accelerator control systems has been rapid. However, the evolution from total manual control systems to complete computer control systems¹⁾ has not been accompanied by an equivalent advance in the techniques of computer control. Some of the newer systems though controlling the equipment through the computer retain manual features that still encourage operators to adjust the accelerator by such actions as turning knobs. Thus computer control of accelerators does not necessarily imply automation. The automation of an accelerator should rather be understood as the elimination of actions and decisions that operators have to make during the accelerator's set-up and exploitation. Automatic procedures can range from the simple task of setting magnetic fields, through beam steering to the difficult problem of the complete set-up for a period of 'physics'. Most accelerators can be regarded as autonomous once they have been set up and adjusted for the relatively long physics periods. It is during the set-up phase that the operators benefit most from the application of automation. It is mainly in this area that attention has been focused in the ISR.

2. WHY THE ISR NEEDS AUTOMATION

The evolution of the ISR and the resulting improvement in performance has introduced an increasing complexity in operation that has been a natural incentive towards automation. The nature of accumulation and acceleration processes in a proton storage ring is generally very sophisticated²⁾. To reach highest luminosity, the number of particles stacked in a given phase space area must be maximized while the transverse emittance must be kept low. The radiation 'background', originating from distorted orbits, non-linear resonances, betatron coupling, etc. must be minimized and Landau damping is essential to avoid transverse instabilities. These considerations require a precise control of all beam and accelerator parameters over the complete machine aperture across which there is a 4% momentum spread.

A further complexity arises from the sensitivity of the ISR to long term variations in conditions which are difficult to predict (e.g. injector stability). This excludes, to a

large extent, pre-programming and promotes dynamic control based on beam observation.

The long cycle time of storage rings (preparation of the ISR for physics alone may take five hours per ring) which makes a beam loss unacceptable emphasises the need for reliability. These considerations are reflected in the design of the hardware and the security built into the operational procedures and the software. Automation is one aspect of this security in that it avoids unsafe techniques such as search by trial and error and minimizes the possibility of human error.

A further and obvious goal is to minimize the time taken in setting up the accelerator and in recovering after shutdowns, changes to machine operating conditions etc.

3. CONFIGURATION OF THE PRESENT CONTROL SYSTEM

The ISR computer control system³⁾ is of a conventional design, being a functionally distributed system consisting of four on-line computers connected by low speed datalinks.

A subsystem dealing with the vacuum monitoring is almost completely independent, whereas another dealing with magnet power supplies is tightly coupled to the central computer which manages all the main control software. Alarm and logging programs run in their respective subsystems under the surveillance of a central alarm processing subsystem installed on the fourth computer.

4. WORKING WITH MACHINE PARAMETERS

One of the guiding principles of the ISR control system is that operators work in terms of machine parameters and not equipment values. For example, beam positions can be expressed in millimeters and tune correction is performed by specifying the required changes in quadrupole, sextupole and octupole terms. This philosophy has led to the evolution of the control system towards the global treatment of many equipment parameters in order to relate them to a single accelerator parameter and vice versa.

5. A MODULAR APPROACH

Modern authorities⁴⁾ on the implementation of large complex systems strongly advocate a modular approach. Modules should exhibit maximum independence from each other. They are linked together to form a hierarchal structure where the higher ranked module has the broader function to be executed. The control system should be composed of well-defined and well-documented modules with standard interfaces from both a user (operator) and an equipment point of view. Typically, the lower interface deals with equipment parameters and the higher interface is specified in terms of accelerator parameters.

The set-up phases of the accelerator have corresponding modules in the control system that, at present, the operator calls into action. Identification of modules is straightforward; a module corresponds to a high-level function that the operator wishes to perform. Injection optimization is one module, measurement of the tune and its correction forms two modules that when applied sequentially perform automatic correction. The steering of the beams to maximize luminosity and minimize background is one module that functions automatically. Measurement of beam losses, the closed orbit and its correction, movement of the scrapers to touch the beam are all modules. With the evolution of such modules the control of the ISR has long since outgrown the need for direct control of the machine hardware by the operators.

6. MODULE CHARACTERISTICS

The modules that the operator requires are, in general, non-trivial. The exclusive use of an efficient high-level programming language CORAL 66⁵) has undoubtedly aided the development of these modules and the control system software. The readability, ease of construction and reliability given by such a block-structured language has simplified the problems of implementation. Furthermore, such a high level language has proven essential for maintenance since modules evolved as the understanding and requirements of the accelerator developed. Production of these modules has not been restricted to specialists nor to programming professionals. Interested parties have written their own modules following the established standards.

Each module performs its duty in a variety of ways that are determined by an associated parameter list which is a character string containing any number of parameters in any order. Individual parameters are identified by standardized keywords. For example, all modules requiring an input file will have the input file name specified as 'IF = input-filename' in the parameter list. Each module is documented to describe its use, the menu of parameters that it recognizes and their effect.

Modules with their parameter lists can be assigned to buttons on the operator's console with the result that pushing a button invokes a module with its attached parameter list. This is the usual mode of operation; typing is rarely needed.

Testing is simplified by the modules having well-defined interfaces allowing easy simulation of their environment in an off-line development computer. Nevertheless, modules performing control functions are incorporated into the on line system only after a period of machine development where the module is checked out under beam-handling conditions. This has provided a considerable stability to the control system, a high reliability for the modules and a high degree of operator confidence.

Modules are linked together by a command language processor (called PROC⁶) which allows conditional sequencing of actions and provides string processing facilities to generate parameter lists. Modules may return result strings which are mainly used to indicate the success or failure of the requested operation. The real results returned by modules are rarely single values but are typically arrays of values such as current changes of power supplies needed to produce a tune correction. These are transferred between modules by a simple but flexible database system based on the existing file structure.

Modules run in an environment which is set up by a simple operator command at the beginning of a run. The command initializes the database with the relevant machine parameters; both predefined and calculated, such as various magnetic functions at the beam position pick-ups, the rest mass of the beam particle, the tune and the chromaticity.

This database provides necessary default values for the parameters used by a module allowing the same command to be used to invoke the same modules under a wide variety of conditions. Furthermore, sequences of modules linked together by a PROC program and callable from a button, can be used under different machine conditions without operator interaction. Accelerator operators have responded quickly to the PROC facility and, following operational experience, have developed routines that have progressively brought the ISR closer to complete automation.

7. AUTOMATION OF SMALL SYSTEMS

Ease of automation depends on the flexibility and power of the control system and on convincing people of the feasibility. Initial steps in automation tend to mimic the steps of the operator and though this does not guarantee that the optimum solution will be found it avoids human errors. As each particular problem evolves then the automated process can be improved. One example of this is the minimization of the transverse beam size after injection, an automatic process that started as an operator replacement algorithm.

In the early days of the ISR, this optimization was done by the operator using the computer to make small changes in injection angle and position whilst observing the residual injection error betatron oscillations. Minimal values could usually be found for each variable of each plane in a total time of about 1 hour. The first improvement was the connection of this injection error signal to the computer and the automation of the process as an operator replacement algorithm using a simple fitting technique to find the injection minima. This gave both a gain in reproducibility and a reduction in time to around 15 minutes. The final step involved the detailed analysis of the process which along with the availability and mathematical analysis of the single turn orbit permitted the implementation of a non-interactive reproducible optimization, taking roughly 2 minutes.

It is important that the automation of complex systems rest on solid foundations. Where possible, initial conditions should be made reproducible in order to reduce the number of variables that later need dynamic correction. An example of this is provided by the modules that cycle the numerous ISR magnet power supplies to give consistent hysteresis effects in the magnets.

The advantages that can be derived from reproducibility are well illustrated by the procedure used to stack a beam while dynamically applying space charge compensation. At first the compensation had to be calculated from the density profile measurement several times during the stacking process. This measurement was a lengthy procedure susceptible to error (due to signals induced by the beam in the other ring). The operator checked that the compensation was valid and invoked a module to apply the changes to the currents of the magnet power supplies. Using the fact that stacks can be made with uniform density, a module was implemented that calculates the necessary compensation as a function of the total stacked current and automatically applies it. Checks are incorporated to ensure that the total stacked current and its position are correct. Errors are signalled to the operator and the process interrupted. The result is a procedure that avoids the lengthy density measurement and is used regularly for normal physics stacks.

Stacked beams in the ISR are regularly accelerated under computer control⁷⁾. For low intensity beams this is a completely automated process involving but one module. However, for high intensity beams a large number of additional conditions have to be fulfilled which entail checks on the tune, orbit, particle losses, etc. At present, these checks are invoked by the operator. For the acceleration module to command these checks itself, is the essence of full automation.

8. TOWARDS FULL AUTOMATION

The implementation of full automation is being developed in two parallel ways. The first is the enhancing of the modules themselves, the second the linking of modules into

modules of a broader nature which are higher in the hierarchy. There is also the opposite trend in that new operating procedures of the accelerator render a previously automated process only partially automated until such time as the extra checks and control functions have been integrated.

The first line of development encounters problems of a local nature, a typical example being the quantification of the actions of the operator. In the measurement of the tune diagram of a stack a frequency plot of the Schottky noise is obtained and the points corresponding to the edges of the stack have to be determined in order to calculate the tune diagram. At present the module generates the plot and determines the edges but always presents the result to the operator for approval. Most of the time the module is correct; when it is not it is because the edges are difficult to determine and this is a situation that the module could also recognize. In a fully automated system the module would only ask for approval when it has difficulty in finding these edges.

The ability of modules to assess the quality of the results they produce, and hence the correctness of the decisions they make is an important concept for achieving the goal of full automation.

The second line of development encounters problems of a global nature. Once all the steps in the setting up of the accelerator have modules associated with them and the operators' principal task is to analyze graphical outputs and to handle error conditions, then full automation seems to be near. Unfortunately this is not the case. One of the most difficult aspects in progressing from partial automation to full automation is in quantifying the analysis of the various displays. For example, at the ISR the closed orbit can be presented to the operator who, after inspection decides whether or not to call the closed orbit correction module. This decision is based on the criteria from many different inputs other than the closed orbit display. The closed orbit may be acceptable (i.e. within recognized limits) but due to a background level slightly higher than normal in part of the ring, the closed orbit is viewed with a more critical eye and may be corrected slightly. These considerations represent one of the major problems of full automation.

Thus another important aspect of full automation is the ability to correlate the outputs of many different modules to arrive at a particular decision.

It is not envisaged that full automation will permit the exploitation of the accelerator under all conditions but rather that set-up will continue until an abnormal condition occurs that is outside the scope for automatic correction. The operator would then be informed of the nature of the difficulty and be expected to take steps to overcome it. The abnormal condition may be detectable only at the current stage of the set-up, or it may be a fault condition that has suddenly arisen and invalidates earlier work. To detect the source of the latter a sophisticated alarm and monitoring system, as implemented at the ISR, is essential.

Even when progress has been made to a fully automated system, the modules that perform the natural high-level functions of accelerator control must remain available to allow the vital work of machine development to continue.

CONCLUSIONS

This paper has described one methodology suitable for the introduction of full automation. Barriers are recognized to exist but are not unsurmountable. Often all that is needed to overcome these barriers is the belief that the process can and should be fully automated.

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