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The Software for the CERN LEP Beam Orbit Measurement System

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The Beam Orbit Measurement (BOM) system of LEP consists of 504 pickups, distributed all around the accelerator, that are capable of measuring the positions of the two beams. Their activity has to be synchronized, and the data produced by them have to be collected together, for example to form a "closed orbit measurement" or a "trajectory measurement". On the user side, several clients can access simultaneously the results from this instrument. An automatic acquisition mode, and an "on request" one, can run in parallel. This results in a very flexible and powerful system.
The functionality of the BOM system is fully described, as well as the structure of the software processes which constitute the system, and their interconnections. Problems solved during the implementation are emphasized.

Introduction

The Beam Orbit Measurement (BOM) [1, 2] system is one of the most vital instruments of LEP, and it is potentially very powerful. 504 pickups, connected to 40 VME crates, are distributed all around the LEP ring . Each pickup can acquire a signal induced by the passage of each single bunch of particles and record it in a VME compatible memory card. Each crate is equipped with two such cards, ("Main" and "Secondary"), which can store signals coming from up to 1800 (450 for the secondary) turns. The signals are processed locally by microprocessors in the VME crates (called DSC, from Device Stub Controller), and then finally collected in a single computer to produce the final result (typically, the LEP orbit).
Due to various reasons (limited CPU power in the VME crates, incompleteness of the software, unfriendliness of the RMS68K programming environment on the VME crates and the reorganisation of the CERN accelerator divisions), the potential of the system had never been fully exploited. For this reason, in July 1990 it was decided to upgrade the computer part of the BOM system, both from the hardware and from the software side. Major points of the upgrading were :

1. Replacing the DSC 68010 CPUs with 68030 CPUs equipped with floating point coprocessor.
2. Replacing the RMS68K microprocessor operating system of the DSCs with OS9. The new DSC systems would be diskless and would load system and application programs from a common file server. This would make the overall system cheaper, more reliable and easier to maintain.
3. Using a dedicated Apollo workstation (the BOM Server) to collect the data coming from the DSCs and to deliver the results to the users of the BOM system.
4. Implementing direct network connections, based on the TCP/IP protocol, between the DSCs and the Apollo workstation where the data have to be put together.
5. Finally, a complete redesign and rewriting of the software to be run both on the DSCs and on the Bom Server . This will be the main subject of this article.

Constraints (and flexibility) : How the system works.

When upgrading an existing system, some degrees of freedom are frozen. A preliminary step to perform is to examine the things that cannot be changed; the new system will have to live with them.
In the LEP BOM system, the data acquisition in the 40 DSCs is triggered and synchronized by the Beam Synchronous Timing (BST) system [3, 4, 5]. This system interprets "tasks" written in a pseudo-assembler language. At each LEP turn the BST distributes an identical message to all 40 DSCs. This message contains a part which can be read by programs running in the DSC, and a part directly received by the hardware installed in the VME crate. As mentioned in the Introduction, in each crate there are two "Acquisition" memory cards. By software it is possible to independently set the access to these memories in one of two modes ,"intern" or "extern". In the "intern" mode the memory is made accessible to the processes running on the DSC CPU, whereas in "extern" mode the memory can receive data from the BOM data acquisition electronics (FADCs). The FADCs produce data every time a bunch of particles crosses the pickup. If the access to a memory is set as "extern", and a certain bit of the BST message received at a given LEP turn is set to 1, then the data produced by the FADCs during that turn will be written into the memory, together with the arrival times of the various bunches.
The pickups close to the intersection points are equipped with Wide Band electronics, while the rest of the pickups are equipped with Narrow Band electronics. The Narrow Band pickups can measure, during the same turn, the signal generated by each bunch of each beam circulating in LEP. The Wide Band pickups only measure the signal generated by bunches of a preselected beam.
The fact that the system has two acquisition memories provides a certain flexibility. It is able to perform two different operations at the same time, one in the Main memory, the other in the Secondary memory. The two memories can be considered as belonging to two different instruments.
There are, however, a few constraints which have to be dealt with :

1. While the Narrow Band systems can acquire both beams at the same time, the Wide Band systems cannot. Their settings have to be changed if one needs to change the type

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of beam to be observed.

2. The hardware setting of the pickups is common for all the pickups in a given DSC and for both acquisition memories.
3. The BST message received at each LEP beam turn will always be the same for all the DSCs.
4. Two other possible limiting factors are the data processing capacity of the BOM CPUs and the data transfer capacity of the network connecting the BOM crates to the Apollo BOM Server.

Requirements : what the BOM should do

The starting point of the new BOM software design was the analysis of the requirements. This implies the definition of the operations the system is expected to perform, and of what is important to the users who perform the different operations.
Several different operations can be performed by the BOM System, by acquiring different sets of turns and by extracting different information from the acquired data. We briefly describe each of them.

- **Closed Orbit Measurement.** "Acquire a given number of turns and, for each pickup, compute the average beam position. "
  The user must be able to specify the number of turns, and to tell the system if data coming from the two beams have to be mixed or not.
  The average is made over all bunches of a given beam, or over all bunches of both beams if the result has to be mixed. This is the most important of the BOM operations, because it is used for correcting the orbit. It is therefore very important that the BOM System should be able to perform it quickly and reliably.
  This operation requires synchronisation between the 40 BOM crates : we need to acquire data from the same turns all around LEP. Therefore the start of the data acquisition must be triggered by the BST.
- **Beam Trajectory Measurement.** "Select a beam. Acquire a given number of turns. For each pickup compute the beam position of each bunch at each turn. "
  Again, this operation requires absolute synchronisation between the 40 BOM crates. In this case it is particularly important that every pickup acquires data from the same turns
  The Trajectory Measurement becomes very important when, for one reason or another, the beam does not survive inside LEP. In this case the acquisition will be triggered at the injection of particles into LEP, so that the behaviour of the beam immediately after the injection can be analysed.
  Typically one is interested in a very few number of turns (8 turns are enough to get the first revolution for each bunch).
- **Beam Position Monitoring at Experiments.** "Every 60 seconds, acquire and average the beam position in the pickups closest to the intersection points with experiments (Wide Bands), and derive the beam position at the interaction points"
  This operation is only important when LEP is running in Physics mode, and it has to be performed only on the Wide Band crates.
  One can note here that if the BOM system periodically measured the Closed Orbit, the same data could also be used to perform this measurement.
- **Continuous Recording** (for Post Mortem Beam History or other) "Every n turns, acquire 1 (or m) turn(s). On request, or on a special event, stop the acquisition." The aim of this operation mode is to be able to reconstruct the behaviour of the beams before a given event (e.g. beam loss). The data processing will depend on what the user is looking for.
  One should note that, since for the Wide Band only one beam can be acquired at a time, the information coming from those pickups will be incomplete. Note also that unless an automatic mechanism like the BST "service request" is available to stop the acquisition in real time, this operation will not be really useful. In fact, if the acquisition takes place every turn, the memory will be completely overwritten every tenth of a second.
  This mode of operation is particularly important during LEP Machine Development.
- **1000 Turns Acquisition.** (for Harmonic Analysis of individual Pickup Data, or other). "Select a beam and a particular bunch. Fill the memory with consecutive turns, for each pickup compute the positions of the selected beam and bunch at the different turns, and store them in a table. "
  The table is then available for whatever analysis is required on the data. It must be possible to start the acquisition after a specified event.
  It could also be convenient to be able to acquire a turn every n turns, to observe the beam over a longer time interval. In fact, 1000 consecutive turns represent only 89 milliseconds.
- **Calibration and Simulated orbit.**
  "Calibration : With no beam in LEP, use the ad-hoc BOM hardware to determine the gains and the offsets for each pickup. Save these values, and detect suspicious pickups."
  "Simulated Orbit : With no beam in LEP, use the ad-hoc BOM hardware to simulate an orbit with predetermined positions. Check if the measured values match the predicted ones."
  The Calibration was normally used by the BOM hardware specialists, but making it more automatic, it could become a routine procedure for the operators. The Simulated Orbit is used to check the quality of the Calibration.

Some of the operations described are performed on demand, others are executed continuously in background, others are repeated at fixed intervals. The most important operation is the Closed Orbit measurement, which is needed to correct the orbit.

The strategy of the new software

All the described BOM operations consist of two main parts : the *acquisition* and the *processing of the data*. The acquisition includes also the preparation of the system (hardware setting). The data processing includes also, in most cases, sending the data to the BOM Server, which has to collect the data from all

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the DSCs and to make them available to the users of the system. To synthesise our analysis, we have to find a convenient solution to exploit the flexibility of the system (two independent memories in the DSCs) in order to satisfy the requirements (on demand and automatic operations), keeping in mind the overall constraints (only one hardware setting , and only one BST task executable at a time, that means only one *data acquisition* operation performable at a time).
Solving this problem in terms of software means finding a natural subdivision of tasks between different computer processes, both on the DSCs and on the BOM Server.

Processes on the DSCs

On the DSCs we have 4 main processes : one to *Prepare* logically the DSC for the following operations, one to *Set the Hardware* of the DSC to the required conditions, one to *Process the Main Memory* and one to *Process the Secondary Memory*. These two latter Data Processing processes are two instances of the same one, accessing respectively the Primary and the Secondary Memory. All these processes wait for BST messages, and then perform the specified actions. Typically any of the BOM operations will consist of a call to the Prepare process, one or more calls to Hardware Setting followed by acquisition of data in one of the two BOM memories, and eventually a call to the corresponding Data Processing Process, which will read the data from its memory, will produce the result and will send it to the BOM Server if needed.
Other two processes perform useful tasks : the *Auxiliary* process and the *Creator*. The Auxiliary process performs all sort of miscellaneous operations (setting the DSC time, loading new calibration factors, doing offline analysis on data already acquired) on reception of the corresponding BST action code. In particular, it performs the harmonic analysis on the table produced by the Main Memory process as a result of the Multiturn Acquisition. The Creator process starts all the others, restarts them if they die, and creates the shared memory areas via which the other processes can share information.
An additional independent process is an RPC [8] server for diagnostic access to the hardware of each BOM crate from PCs and Apollos (The RPC is used in this case because the Xenic PCs found close to the equipment do not support TCP/IP sockets).

Processes on the Apollo BOM Server

On the Apollo BOM Server two processes , the *Automatic* server and the *Demand* server, share the BST resource via a semaphore. While the Automatic server executes periodically commands from a command table, the Demand server is activated by the Interface server. This latter process constitutes the interface between the BOM Server system and the users. Via a library of functions they can, among other things, trigger a new closed orbit measurement, ask for the result of the latest or the next acquired orbit, enable or disable the automatic server. Two other processes, the Collector and the Receiver, complete the building blocks of the BOM Server. The Receiver receives data from all the DSCs directly into a shared memory, from where the Collector can read and treat them. The Collector is also signalled by the Demand or by the Automatic servers every time an operation (e.g. Closed Orbit) starts, and tells the Interface every time the results of an operation are completed. The Interface will then deliver the result to the user(s) waiting for it, if any. All these processes are started by a Starter process, which surveys them, and communicate through shared memories (MOPS) and message queues.

Implementation Problems

The implementation of all these ideas required a considerable amount of work. We had to find our way through several foreseen and unforeseen problems. Some have been solved satisfactorily, others not yet.

- SPEED.
  In order to improve the performance of the DSC software, special care has been taken to avoid repeated calls to subroutines with high number of arguments. Also "register" variables have been used in an effective way. By following these prescriptions, it was possible to save an order of magnitude in the DSC processing time.
- PARTICLE IDENTIFICATION.
  The Narrow Band Pickups acquire signals coming from each bunch of each particle. The software analysing these signals should be able to distinguish between electrons and positrons. For this reason, the relative arrival time of each bunch with respect to the LEP turn clock signal is recorded in memory together with the data. This time (called *"fine-time"*) is measured in units of 400 nanoseconds, and it can be compared with reference tables for each pickup, to identify the different bunches and to reject parasitic signals. When all the bunches are present, the particle identification is easy, because the arrival order of the bunches if predetermined. When some bunch is missing, the identification becomes critical for the Narrow Band pickups closer to the intersection points, because the time interval between bunches of the two particles is only around 660 nanoseconds, and the turn clock signal arrival time can be wrong by up to 200 nanoseconds. To try to solve this problem, we first analyse the data for a pickup far from the intersection point. From this, we produce a table containing the different bunches in LEP, together with the difference between the theoretical arrival time and the measured one. This table enables the program to correctly identify the particles even in the most critical pickups.
- INSTALLING THE NEW SYSTEM.
  The transition between the old and the new system was not a single step one. It had to be done progressively, keeping the whole system operational, and replacing old parts with new ones as soon as they were ready. Therefore it has been necessary to make all the new software produce results compatible with the old one. This has been achieved by writing a process (the *BOM Listener*) on the Apollo BOM Server. The BOM Listener receives from the Collector all the messages that should have gone to the Old Collector on the PC, and sends these messages to it. Another point where compatibility with the old system was taken into account was in writing the new BST tasks, because they had to be understood by both systems.
- NETWORK TROUBLE.
  The most serious problem was the network communication between the DSCs and the BOM Server Receiver. We are currently using the TCP/IP communication protocol, connecting each DSC to a Receiver program on the Apollo.

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We do not have a large amount of data to send (typically less than 500 bytes per DSC), but we meet serious limitations. To make a long story short, we need to run 8 Receivers on the Apollo, so that they will receive data from 5 DSCs each. We found that if we tried to send all the data packets from the DSCs at the same time, a large fraction of the packets were arriving with large regular delays (typically 13, 26, 40 and 92 seconds), and occasionally some packets were lost. The regularity of these time intervals implies that we were observing some "wait and retry" mechanism implemented inside the TCP/IP software. In our set up this effect started to manifest itself when more than 15 DSCs were installed. Our first attempt to circumvent this problem has been to introduce additional delays in the DSCs, so that they do not try to transmit all at the same time. Our best result has been achieved by spreading the transmission of the DSC packets over around 10 seconds, in which case most arrive in a spread of 12 secs, with only a few arriving after around 25 secs.
To improve this performance, an alternative data transmission has been developed, based on a simple protocol sending raw Ethernet packets from the 40 DSCs to a central collector OS-9 system on the same Token Ring. A single TCP/IP connection then connects this system to the BOM Server Apollo. This system seems to reliably deliver all 40 replies within at most 12-13 seconds, and often quicker (the best observed performance was 7 seconds) ; we are gaining operational experience with it.

- INVOKING THE BST SYSTEM.
  The BST system is currently activated through a remote procedure call to a dedicated PC. Up to a few seconds are lost in establishing the connection to this system. Moreover, occasionally the calling program never returns from the RPC routines, and it has to be killed.
  We are currently porting the BST system to the OS9 environment.

- NETWORK FILE SYSTEM FOR THE DSC.
  Our DSCs are diskless and boot from a centralized fileserver. Initially, a reduced version of the Network Disk server developed in the LEP Aleph experiment [6] was developed by D. Mathieson to run on OS-9. This support work was essential, because it allowed tests with a full 40 DSC system to be carried out during the 90-91 winter shutdown of LEP, before a usable NFS was available for OS-9. This system was also used in LEP operations until June, when the NFS on OS-9 seemed sufficiently stable to transfer to using it.
  This latter system is far from being perfect. In order not to overload the fileserver and the network, we have to wait around 10 seconds between the boot of two DSCs. With 40 DSCs, this means around 7 minutes to boot all of them; yet not all successfully reboot at the first attempt. A more serious problem is that the online use of the system is almost impossible; if a few DSCs want to access files at the same moment, very often the NFS gets stuck and it is unavailable for about 30 minutes. A better configured fileserver, closer to our DSCs and more dedicated to the BOM , is planned to be installed.

Results

The transition from the old to the new system has taken place in several steps. First, in mid April 1991, the first version of the Apollo BOM Server was installed, together with the first OS9 Wide Band DSC. At the beginning of May the remaining 7 Wide Band DSCs were installed, and since this time data from the Wide Band systems has been sent to the Apollo, which forwarded it to the old BOM Collector PC. The next step was to use the first Automatic Server to periodically produce the data needed to determine the position of the two beams at the interaction points [7]. This was accomplished in May. Also in mid June the 16 Narrow Band DSCs which share the same network infrastructure with the Wide Band DSCs were installed during one afternoon. At the beginning of July, profiting from the last access hours during a short shutdown, the remaining 16 NB DSCs were rapidly installed and connected to the LEP Token Ring, using the freshly arrived IBM Ethernet-Token Ring Bridges. In August the new Multiturn Acquisition and Harmonic Analysis facility was first demonstrated. After the holidays, work went into improving the Calibration procedure and producing a second version of the BOM Servers. Currently the Automatic Orbit Acquisition is running, producing a new orbit every 60 seconds. The latest orbit produced is available to the LEP operators within seconds. Applications based on the repeated orbit acquisition have been written, for example to monitor and display continuously the position of the beams at all the Wide Band Pickups in the Experimental Areas.
To summarise the results

- Thanks to higher performance DSC CPUs and to software better optimised for speed the data processing time has been reduced by a factor of 25 . This means that it is no longer impractical to average the Closed Orbit Measurement over a large number of turns. This turned out to be very useful when we discovered, via a Multiturn Analysis, that there was strong 50 Herts noise in LEP (generating a typical peak to peak oscillation of 0.5 millimeters). The period of this oscillation is 224 turns, so, in order to average it out, we now measure the orbit over 224 or 448 turns. The processing time takes only a very few seconds. The overall time from when a new orbit measurement over 224 turns is asked to when the result is made available to the operators is now around 22 seconds (using the above mentioned alternative data transmission schema). We plan to reduce it to 15 seconds next year.
- A new algorithm has been implemented, with good results, to distinguish between electrons and positrons in the Narrow Band Systems. This makes it possible to acquire an orbit of a specified beam. It was possible in this way to show the saw_tooth effect due to the beam losing energy when emitting synchrotron radiation.
- The Multiturn Acquisition, together with the Harmonic Analysis facility, has been used successfully to measure some physics parameters of LEP (phase advance, dispersion,..). The effect on the injection kick on the orbit can also be examined, and instability in the beam detected and studied. A Fast Fourier Transformation can be also performed on each pickup's data , to show possible perturbations.
  By analysing data from the Multiturn Acquisition it was possible to localize the source of the 50 Herts noise.
  This facility also enables us to check the quality of the

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data coming from the different pickups, and makes the detection of bad pickups easier. By examining results from such an acquisition , we were able to detect a pickup which was wrongly cabled (the vertical and horizontal positions were interchanged), and another where two cables were short-circuited.

- The Automatic Orbit Acquisition, by which a new orbit measurement is produced every minute, makes life easier for the operators. It also constitutes the base for any LEP orbit statistics program. By a simple call to a function, any program can get all the data coming from the latest acquired orbit within seconds.
- The Calibration, which in the past was not very user friendly and required half a day of work, now takes 10 minutes and does not require any specialist intervention. It also updates a database, through which pickups which were not correctly calibrated will be marked as bad in the orbit data provided to the Operators.

Future Improvements

Of all the initial requirements, only the Continuous Acquisition of data has not yet been implemented.

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