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The Beam Synchronous Timing System for the LEP Instrumentation

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The beam instrumentation group of LEP has constructed a number of detectors distributed around the collider : these instruments are interfaced to approximately 100 VME based computers which acquire and process data autonomously. In order to ensure the coherence of a measurement and to correlate measurements of different instruments, it is essential that the data are acquired at the same moment on all the systems. The Beam Synchronous Timing System ensures this by broadcasting messages describing to all instruments the action to be performed. The instructions are guaranteed to arrive at exactly the same moment to all stations around the 27 km circumference by careful compensation of the delay for each station.

The heart of the system is a commercial 25MHz 68020 based VME module coupled to an inhouse designed message assembler : these are able to synthesize instructions for up to six different kinds of instruments in a single LEP revolution (89 μ s). Each listening station provides the hardware with pulses derived from the incoming message, filters the messages according to the addresses and passes them to real-time tasks which set the hardware or acquire the data.

A reverse channel, peripheral station to control room, allows up to eight different signals to inform the master of locally detected events such as beam loss or high background. Special recovery instructions can then be broadcast.

1. INTRODUCTION

1.1. General

CERN, the European Organization for Nuclear Research, has constructed a Large Electron Positron (LEP) collider on the Franco-Swiss border near Geneva^[1]. The underground tunnel has a circumference of approximately 27 km, at a depth varying between 50 and 150 meters below the surface. There are 8 access points regularly distributed around the machine ; in addition, 2 small blind caverns are located at roughly one third and two thirds of the distance separating any two consecutive access points, thus making a total of twenty four distributed locations where the electronics for controlling the beam instrumentation of the collider is concentrated. Each location, called a STATION, controls the instrumentation spread over about 1/24th of the total machine length.

Two sets of 4 equidistant bunches, one of positrons and the other of electrons, circulate in the machine in opposite directions. Once the beams have been accelerated to the nominal energy, the results of the collisions of e^+/e^- bunches are observed by four large experiments, L3, ALEPH, OPAL and DELPHI.

1.2. Communication environment

In order to reduce cabling costs around LEP, the interconnection for communication between all these locations has been realized utilizing Time Division Multiplex (TDM) techniques, which are widely used in telecommunication all around the world ; the communications system conforms to CCITT G700 series of Recommendations^[2].

Time Division Multiplexing is based on modern technology offering more and more products for digital transmission. It gives to the user a means of transporting his information on a shared physical link, thus reducing considerably the communication cost.

The integrated communications system uses optical fibre cables in surface ducts and, because of radiation, coaxial cables in the ring tunnel.

1.3. Control environment

Any beam instrumentation STATION is under the control of one Process Control Assembly (PCA), which is interfaced on one side to an IBM Token Ring carried by the communications network and on the other side to the Equipment Control Assemblies (ECA) through the MIL-STD-1553B standard multidrop highways^[3].

A General Machine Timing system distributes everywhere date, time and machine events^[4] (fig 1).

The PCA, presently an Olivetti M380 running XENIX, has two major roles for the equipment : it serves as an access point to and from the control network and it allows its local surveillance.

Each ECA is made of a VME crate containing two different sets of modules, one basic and the other dedicated. The basic set is composed of :

- one Themis TSVME106 CPU module containing an MC68010 processor, 1 Mbyte of DRAM, 500 Kbytes of battery backed-up SRAM, an MMU and running the Motorola RMS68K operating system kernel,
- one Remote Terminal Interface module which connects the ECA to the MIL-STD-1553B bus,
- one General Machine Timing receiver module which decodes the distributed events concerning the machine with a resolution of 1 ms and a jitter of $\pm 1 \mu s$, thus allowing general equipment such as power supplies to be synchronized to relevant machine events,
- one Beam Synchronous Timing module which behaves in time with the beam ; it is fully described in the next paragraphs.

The dedicated set is composed of both standard and inhouse modules which have been selected for the particular instrument.

2. NEEDS FOR A BEAM SYNCHRONOUS TIMING SYSTEM

The synchronization of events in accelerators is a fundamental problem which causes difficulties for the operator and also for the expert whenever something goes wrong.

In matter of synchronization, if we consider one equipment formed of a set of geographically distributed beam monitors having to behave in time (typically, the Beam Orbit Measurement system), one may identify the same type of problems that are encountered in orchestras. Both are entering the following sequence :

- A request is made by an operator or a process triggered by some specific conditions (time, machine state, alarms, ...). This is for musicians the tune which the conductor wants to be played.
- The execution is set at a specific time determined by the conditions imposed by the request. In terms of music, the partition is put on the music stand.

- The execution is launched all around the machine in strict time synchronized to the beam. The tune is played in time with the baton of the conductor.
- Data come back to the operator. The music comes to the ears of the listener.

In modern accelerators, the need for standard and comfort has lead to select powerful operating systems which offer the best performance/price ratio. Today, UNIX-like systems offer everything but real time in the sub-hundred-millisecond region.

In terms of time, the first and the fourth step of the sequence is not very constraining ; no doubt UNIX can make it. The second step may become a challenge if the request is made with a short notice with regard to execution ; this is the case when the decision is hooked up to random events. The third step is clearly out of reach of UNIX.

The need for another means of communication being clear, the choice was between the transmission of a simple pulse or a more sophisticated message, both being synchronized to the beam and distributed around the machine at the beam revolution frequency. A clear advantage of the message transmission is the capability of reducing the dead time of the equipment concerned. The communications network needed for the distribution of pulses can also carry messages and so a message-based transmission was chosen for the Beam Synchronous Timing (BST) system^[5].

Some kind of fast interrupt is often needed, for example to stop immediately the movement of collimators whenever a loss of beam is detected by the intensity monitors. This requirement may easily be satisfied by providing for the insertion of a Service Request by any Station, taking full advantage of the synchronized message approach.

3. DESCRIPTION OF THE BST

3.1. General

The general layout of the BST system is shown on fig 2. The heart of the system is the BST Master. A message is generated for every period of the beam revolution frequency, is sent to all the beam instrumentation Stations and finally returns to the BST Checker for detection of possible corruption ; the Service Request part of the message is then scanned to detect the presence of a demand which will be passed on to the Master.

The propagation time is compensated at the level of each Station, a jitter of ± 50 ns with respect to the beam being attained using PLL techniques and then is delivered to the user equipment.

3.2. Message Generation

3.2.1. Message Structure

The message generated by the BST Master contains four main fields (fig 3) :

- the first field is a 12 bit header serving for message transmission synchronization purposes and for LEP turn clock generation,
- the second field is empty when it leaves the Master and its single byte may collect a maximum of 8 Service Request bits when passing through the twenty-four beam instrumentation Stations.
- the third field is intended for the hardware and its 2 bytes are directly distributed on the P2 connector of the VME crate of the ECA ; the 16 bits are used individually and their allocation depends on the equipment installed,
- the fourth field is intended for the ECA application software and its 5 bytes contain information which will be transmitted to the CPUs in the local ECAs. The 40 bits are further divided into variable length slices which are individually attributed to a specific equipment. Data and control information are contained in each slice.

Fields and bytes are separated by one "0" bit delimiter.

3.2.2. Sources of synchronization

The different requirements are :

- the generation of the BST Master message every $88.92 \mu\text{s}$, which is triggered by the beam revolution frequency signal delivered by the LEP RF equipment,
- the synchronization of the BST Master with injection events, which are taken from "Injection Warning" signals delivered by the SPS injector RF equipment,
- the synchronization with time or general machine events which are decoded from the GMT,

- the synchronization with operator actions or with a process request which is received as a message transmitted on the control network.

3.2.3. *BST Master*

The functions of the BST Master are carried out by four modules (fig 4) :

- a fast CES FIC8230 CPU module^[6], delivering the message to be sent to each instrument every turn,
- a BST Message Assembler (BSTMA) module^[7], assembling, serializing and delivering the message to the communications system,
- a Programmable Delay Module (PDM)^{[8],[9]} used to generate the pattern for bunch number recognition,
- a BST Service Request (BSTSR) receiver module delivering the interrupts collected from the Stations to the BST Master.

Every 88.92 μ s, the FIC has to inspect a set of tables indicating whether or not there is a program active for each of the sixteen different instruments which can be BST users at the same time ; if the program is active, it has to interpret the instruction and put the message for that instrument to the BSTMA.

The BSTMA contains a message memory for sixteen 32 bit wide messages, one per instrument, which is refreshed every turn by the FIC. If the FIC does not produce the message within a certain time, the BSTMA takes the initiative and generates an empty message. In addition to the message memory, the BSTMA contains four down-line loadable tables which indicate where each bit of the BST message is to be taken from in the message memory. Thus they form indirection tables, the first one containing the pattern for an empty message, the second the operational table and the last two are used for test purposes.

The PDM allows the storage of a pulse train sequence which is repeated at the beam revolution frequency. The BSTMA, which receives both the pulse train and Injection Warning signals, can determine the number of the bunch being injected. This information is then passed on to a status register which is used by the instrument program to synchronize with injection.

The last module receives the service requests generated in one or more Stations. It interrupts the FIC which must switch to a predetermined program linked to the expected request.

A specially designed simple assembler-like language provides the following facilities :

- a message can be transmitted, repeated a specified number of times,
- a delay of a specified amount of LEP revolutions can be generated,
- synchronization with injection,
- synchronization with GMT events.

A set of software tools allows the writing and the downline loading of the programs. Additionally, the pulse train pattern stored in the PDM and the four indirection tables can be loaded at any time.

Any computer on the LEP control network can request the execution of a particular BST program, selected from a predetermined set of available facilities ; the PCA in charge of the BST Master will accept or reject the request depending on possible priority clashes.

3.3. Message Transmission

3.3.1. Transport

Every 88.92 μ s the BSTMA delivers a message to the BST/TDM interface^[10] which links it to the TDM network in a full duplex mode (fig 5). The message is HDB3 coded and synchronized to the TDM channel rate of 2.048 Mbit/sec. The BST/TDM provides, in addition to basic interfacing, a fine path-delay compensation with a step of 62.5 ns which can be set through the control system (see section 3.4.1. for the coarse delay compensation), and a Phase Lock Loop (PLL) circuit to reduce the intrinsic jitter caused by the TDM to a value not greater than ± 50 ns.

3.3.2. *BST Checker*

The BST messages are delivered to all the beam instrumentation Stations in turn and then come back to the BST Checker (fig 2), through a BST Receiver (BSTR) module. One fast CES FIC8230 CPU module compares the messages generated by the BST Master before and after transmission all around LEP. Two circular buffers hold the sequence of messages. When a mismatch occurs, or a message inconsistency is detected, recording is switched to a special buffer and continued for a number of turns. A program logs the error and part of the buffer content on disk and launches a check. The BST Checker is also used to validate any Service Request addressed to the BST Master.

3.4. **Message Reception**

3.4.1. *BST Fanout*

The FANOUT module^[11] has been designed to provide a means of decoupling the different users in the same Station ; in addition, the messages may be delayed internally by an integral number of LEP turns, to compensate for large delays in the transmission.

3.4.2. *BST Receiver*

The BSTR^[12] (fig 6) is embedded in the ECA. It checks the presence of a message every 88.92 μ s and increments one 15 bit turn counter : the passage to zero of which is compared to a BST Master generated MESSAGE SYNC bit signal. The message is split into two parts. The first part gives signals which are applied to the P2 connector of the VME to drive the hardware. The second part is filtered by a mask register which is set by the CPU in the ECA crate, upon request of the specific equipment, application ; the resulting message, when not empty, is transmitted to the CPU which, in turn, will inform the appropriate process.

As a result, the unidirectional messages provide following actions :

- they drive the hardware in strict time with the beam,
- they bring commands and data to the application processes within 2 ms, considerably less than the time uncertainty of the control network.

The integrity of the transmission is permanently monitored by the BSTR, which interrupts the CPU for any detected fault. Errors are treated according to their gravity. Fatal error recovery is individually carried out by the PCA in each Station. A program is launched which halts the BSTRs, resets all their registers and commands to go back to RUN. This action is only effective at the arrival of the MESSAGE SYNC bit signal.

4. FIRST EXPLOITATION RESULTS

At the startup of the machine, a few days were needed to adjust all the delays, coarse and fine, in the twenty four Stations. This was done using the beam for reference, which of course creates some difficulty when one is simultaneously commissioning the machine for the first time ! The alternative would have been the implementation of some very sophisticated simulation, which would have cost a lot of money and effort ; the economy was worth the inconvenience.

At present, the features of the BST system are only partly exploited. No limitation has yet been found. The main application is for the Beam Orbit Measurement^[13] system which takes advantage of the major features. Single turn trajectory or orbit measurement of individual bunches of either polarity may be displayed ; distributed transient recording is not yet implemented but this is easily possible, using the Service Request facility.

About forty errors per day are recorded, giving a message error rate of 4×10^{-8} or a bit error rate of 4×10^{-10} .

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CONTROL ENVIRONMENT

Figure 1

GENERAL LAYOUT OF THE BST

MESSAGE STRUCTURE

Figure 3

Figure 4

Figure 5

BST RECEIVER

Figure 6