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The Design and Operation of the Slow Controls for the DELPHI Experiment at LEP

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Abstract

The slow controls of the DELPHI detector enable a single operator to oversee the proper functioning of the apparatus and to diagnose faults as they occur. The hardware and software of this system, as well as their interface to the experiment and the operator, are described. Finally, we attempt to draw some conclusions from seven years' design work and the initial four years' operation of DELPHI.

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1 Introduction and Overview

The DELPHI[1] detector has been equipped with an automated system for monitoring and controlling technical aspects of the experiment, such as high voltages and gas supplies, for reporting and acting on changes in the status of the detector or its environment, and for maintaining the safety of the equipment.

This **slow controls** system should be distinguished from the **data acquisition** system (DAS) [1], which is responsible for the digitizing and recording of each physics event — the products of the electron–positron collision. The emphasis of the data acquisition system is on efficient triggering and fast readout, since the electron and positron bunches cross every 11 μs. In contrast, the slow controls reacts to events that can take from seconds to hours to develop, but is more concerned with reliability, particularly due to its safety requirements.

The overall structure of the DELPHI slow controls system is summarized in figure 1. As can be seen, the system is highly modular and highly distributed with many programs running on both high-level (VAX) and front-end (G64) processors.

The DELPHI slow controls operator makes use of two main graphical displays, shown in VAXstation windows. The status display gives a colour-coded representation of the state of the various detector partitions. These states are defined in the **State Management Interface (SMI)** (see section 8), which is a hierarchical set of objects representing different aspects of the detector as seen by the slow controls system. SMI is also responsible for passing commands (either to the whole of DELPHI or to a particular detector partition) down to the appropriate subsystems which act on them. The error message display shows outstanding anomalies in a textual form, grouped according to detector partition. These messages are handled by the **Error Message Utility (EMU)** (see section 6).

Both SMI and EMU show conditions determined by the **Elementary Processes (EP)** (see section 5.1), which are the lowest-level VAX control programs. The Elementary Processes are also responsible for handling SMI commands, logging state changes to the **Status Update Database** (see section 7.2) for use by the offline analysis, and providing a route for occasional expert intervention, using a user interface, **HIPE** (section 5.2).

The Elementary Processes communicate over ethernet (using the **Remote Procedure Call (RPC)** protocol) with the front-end control and monitoring microcomputers, the **G64** crates (see section 3). The G64s monitor and control a variety of different types of hardware using digital and analog monitoring and control devices. Most high voltage supplies are controlled by an intelligent **CAEN** high voltage unit [2] (see section 3.1.3), which is in turn controlled and monitored by the G64.

The unified **gas system**, which controls and monitors the flows and mixtures of gases supplied to various parts of the detector, and the **GSS** safety system, which monitors the detector and its environment for hazardous conditions, use different structures (see sections 9.1 and 9.2), but are integrated with the rest of the slow controls at the SMI and EMU level. These software links are complemented by a system of hardwired interlocks.

A brief description of the DELPHI slow controls system has been given previously [3]. In this paper we give a detailed and considered description of the systems employed. Additional technical details are provided in a longer version of this paper [4]. For detailed descriptions of the gas and safety systems the reader is referred to separate publications [5, 6].

2 Detector Requirements

The DELPHI detector is one of four [7, 8, 9, 10] installed around the LEP electron–positron collider at CERN. The slow controls of the other three have been described in [11, 12, 13]. LEP is currently operating at around 91 GeV centre-of-mass energy (the Z^0

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[1] ***DE**tector with **L**epton, **P**hoton, and **H**adron **I**dentification*

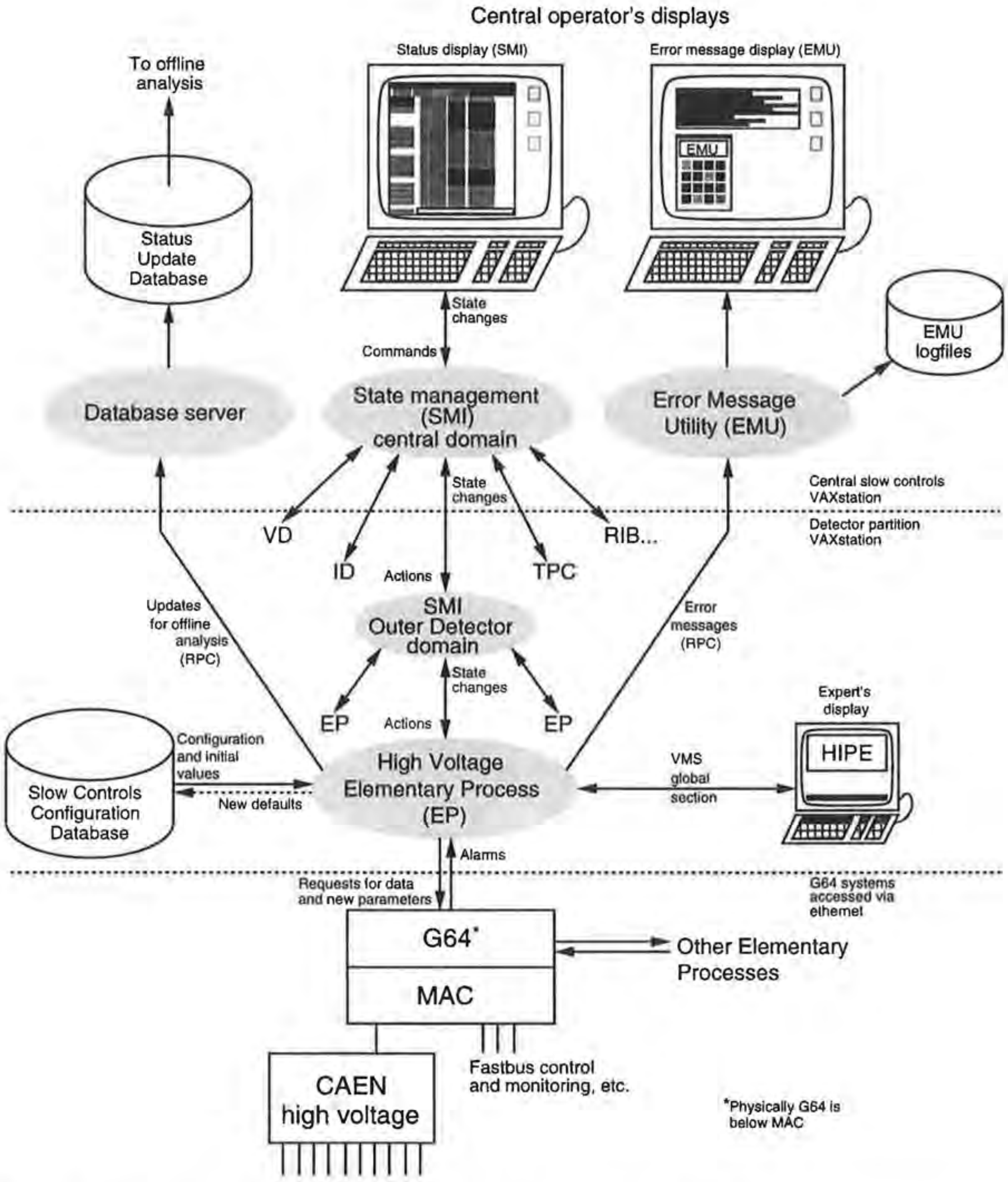

Figure 1: Diagram of the overall structure of DELPHI slow controls system represented by the example of the high voltage control of the Outer Detector.

resonance), and should be upgraded to around 180 GeV (above the W^+W^- threshold) in 1996.

DELPHI is designed as a general purpose detector with special emphasis on particle identification (using the Ring Imaging Cherenkov (RICH) counters) and precise measurement of particle decays close to the collision point (using the silicon Vertex Detector (VD)).

The detector and its front-end electronics are situated 100 m underground in the experimental cavern. The detector has a cylindrical geometry consisting of successive layers of charged tracking detectors (VD, Inner Detector, TPC, and outside the Barrel RICH, Outer Detector at a radius of 2 m), followed by electromagnetic and hadron calorimetry (provided respectively by the High-density Projection Chamber and instrumented magnet yoke), and finally muon chambers (at 5 m radius). A similar arrangement in the endcaps (forward tracking chambers, RICH, electromagnetic and hadron calorimetry, and muon chambers at 5 m on either side of the interaction point) aims for a near-4π solid-angle coverage. The tracking chambers use a solenoidal magnetic field of 1.2 tesla, provided by a superconducting electromagnet (described in section 9.3) just inside the hadron calorimeter.

The various detector partitions exploit different techniques to achieve their aims of identifying or measuring the position, momentum, or energy of the products of electron–positron collisions. Consequently they have different requirements for their slow controls. Here only those aspects relevant to the slow controls are detailed. Full details of the detector itself may be found in [14, 8] or the references given below.

2.1 General Features

Gases are used as ionizing media, allowing electrons to be liberated by the passage of a charged particle. All gases used in DELPHI, despite the different compositions required by differing detection techniques, are provided by a unified gas system, summarized in section 9.1.

Electric fields, produced by high voltages, are used to draw the liberated electrons to an electrode for detection. Most high voltages are supplied by the CAEN high voltage unit, described in section 3.1.3. When large numbers of stray particles are produced by LEP (e.g. while filling the machine), high voltages of a number of detector partitions have to be ramped to a lower value to prevent excessive currents due to large amounts of ionization. This is necessary for the Inner Detector, Time Projection Chamber (TPC), Outer Detector, forward tracking chambers, Barrel and Forward RICHes, barrel electromagnetic calorimeter (HPC), and Forward Muon Chambers. Consequently, speed and reliability of ramping for these detector partitions is particularly important.

Except for the HPC, the voltages and currents of the Fastbus data acquisition crate power supplies are all monitored, and can be switched on or off under computer control. Most detector partitions provide similar monitoring and control for their front-end electronics.

Temperature monitoring inside the detector is performed by the DELPHI slow controls. In the electronics counting rooms, the environment (including rack temperatures) is monitored by the GSS system, summarized in section 9.2.

A summary of the general requirements for each detector partition is shown in the Elementary Process function columns of table 1. Specific details of each detector partition, as they relate to the slow controls, are given below.

2.2 Barrel Tracking Detectors

Tracking of charged particles in the barrel is provided by the Inner Detector, TPC, and Outer Detector. Additional extremely precise measurements are made close to the interaction point by the Vertex Detector.

2.2.1 Vertex Detector (VD)

The Vertex Detector [15] is a high-precision silicon detector giving a measurement of the azimuthal coordinate of charged tracks at three points close to the interaction region, using 73,728 readout strips with a pitch of 50 μm. These require a bias voltage of about 50 V, and detector cooling.

Monitoring of temperature is vital, both in order to prevent damage to the detectors due to overheating, and to keep track of temperature variations which can lead to movement and consequent degradation of the precise alignment. These movements relative to the Inner Detector are monitored both by capacitive probes [16] and by lasers.

2.2.2 Inner Detector (ID)

The Inner Detector [17] provides tracking and trigger information using two components: a drift chamber and a multiwire proportional chamber (MWPC). Both chambers require high and low voltages. The drift chamber uses a carbon dioxide/isobutane/isopropanol gas mixture, and the MWPC uses an argon/carbon dioxide mixture.

The ID uses LeCroy power supplies to provide high voltages for the drift field (not sensitive to LEP conditions), the anodes, and the MWPC. They are controlled using RS232-C connected to the ID VAXstation (via a terminal server), where a special process emulates a G64 system controlling a CAEN. This allows standard VAX software to be used with only minor changes. For more precise measurement of the detector voltages than can be provided by the LeCroys, a digital voltmeter is used.

2.2.3 Time Projection Chamber (TPC)

The TPC [18] is the main tracking detector in DELPHI, providing three-dimensional position information, a momentum measurement (from the track curvature in the magnetic field), and some particle identification by measuring the energy deposited in the detector.

A cylindrical vessel, filled with a mixture of argon and methane, contains an electric cage with a field provided by a 25.3 kV very high voltage. Each endcap is divided into six sectors equipped with multiwire proportional chambers, each containing three planes of wires, a gate grid, a cathode wire plane, and a sense plane of 192 anode wires using a high voltage of 1435 V. Both drift field and sense wire high voltages are provided by CAEN units. Only the sense wire voltages need to be lowered during LEP filling. Special modules are used to measure the current in each sector. High voltage channels are 'daisy-chained' together in the CAEN in such a way that if one channel trips, then all channels of the same polarity trip. Trips are minimized by automatically lowering the volts if the current becomes too high.

Due to the proximity of the heated Barrel RICH, the temperatures are monitored and, if they are too high, the preamplifiers are switched off.

2.2.4 Outer Detector (OD)

The Outer Detector [19] provides the furthest track measurement from the interaction point to improve track momentum measurements. It consists of drift tubes, containing a single anode wire in an argon/isobutane/isopropanol drift gas, bonded together into planks.

High voltages are required for the anode wires. Since the OD is attached to the outside of the heated Barrel RICH, the temperatures and positions of the planks are monitored to check that the alignment does not change.

2.3 Forward Tracking Chambers

Tracking in the endcaps is performed with two similar drift chambers, situated on either side of the Forward RICH, which provide three-dimensional track measurements.

The high voltage systems of both sets of chambers provide automatic trip-recovery. When a channel trips (due to a large current being drawn by excessive ionization in the chamber), this system automatically ramps the channel up again (after a short delay to allow the chambers to recover). If this occurs repeatedly, then the system gives up, leaving further action to the operator (who is kept informed via SMI and EMU).

In addition, the software ensures that ramping is always done in groups of channels so that there are no delays between the start of ramping for different channels within an endcap (FCA) or module (FCB).

2.3.1 Forward Chamber A (FCA)

The Forward Chambers A are mounted on either end of the TPC, and are thus mechanically part of the barrel. Each consists of 6 planes of wires and uses a mixture of argon, isobutane, and ethanol for the drift gas.

2.3.2 Forward Chamber B (FCB)

The Forward Chambers B are positioned outside the Forward RICH. Each endcap consists of two modules which use a drift gas consisting of a mixture of argon, ethane, and ethanol.

Special precautions are taken to prevent the possibility of significant voltage differences between the 12 planes of wires in each module, which are only 1 cm apart. The CAEN high voltage channel for each plane is daisy-chained with the others in the same module in such a way that if one channel trips, then they all trip.

Monitoring of the preamplifier low voltages is required to maintain a balance between sufficient amplification of the signals and noise reduction.

2.4 Ring Imaging Cherenkov Counters (RICH)

The RICH detectors employ an ambitious technique to identify charged hadrons in both the barrel and endcaps. The velocity of a particle travelling faster than the local speed of light in a material medium may be determined by measuring the angle of emission of Cherenkov light. This ultraviolet light is detected using the time projection technique in quartz drift tubes containing a small quantity of a photo-ionizing vapour (TMAE). With the momentum determined from the tracking detectors, knowledge of the velocity allows the particle's mass, and hence identity, to be determined.

Two perfluorocarbon Cherenkov radiators are used: a liquid radiator consisting of C_6F_{14} to identify slow particles and a gaseous radiator of C_5F_{12} (barrel) or C_4F_{10} (endcaps) to identify fast particles.

These fluids [20] (C_6F_{14} liquid, C_5F_{12}/C_4F_{10} gas, methane and ethane used as drift gases, and TMAE vapour) are supplied by a special system controlled by five Siemens process controllers, which perform the particularly careful control and monitoring required by these sensitive detectors. The radiator ultraviolet transparency is checked with a monochromator controlled by G64.

2.4.1 Barrel RICH (RIB)

The Barrel RICH [21] gases are heated to 40°C. This allows the normally liquid C_5F_{12} to be used as a gas radiator, and a greater quantity of TMAE vapour to be present. The temperature has to be controlled and monitored very carefully to prevent condensation of the TMAE by cooling, damage to the detector by overheating, or expansion or contraction which would destroy the detector alignment.

An 80 kV Heinzinger very high voltage unit (controlled directly by G64) provides the electric field to drift photoelectrons to multiwire proportional chambers (MWPC), which are supplied by CAEN units. The drift gas is a mixture of methane and ethane.

2.4.2 Forward RICH (RIF)

The Forward RICH [22] uses C_4F_{10}, which has a lower boiling point than C_5F_{12}, as its gas radiator, and thus does not require the elevated temperature used in the barrel, considerably simplifying the slow controls. A 35 kV FUG very high voltage unit (controlled by a CAEN unit) provides the drift fields, and CAENs are used for the MWPCs. The drift gas is ethane. The temperatures of the gas radiator, drift gas, front-end electronics, and fastbus crates are monitored by G64s, which can cut the TMAE flow or crate power in the event of problems.

2.5 Calorimetry

By converting an incident particle into a shower of secondary particles, calorimeters provide information on the energy of neutral as well as charged particles and can help in particle identification. The electromagnetic calorimeters (HPC and EMF) are designed for electron and photon identification, and the hadron calorimeter (HAC) for detection of other particles.

2.5.1 High-density Projection Chamber (HPC)

The HPC [23] is a drift chamber, highly segmented by lead partitions to induce an electromagnetic shower from the passage of electrons or photons. This technique allows a precise determination of the shower position and energy. The drift gas is an argon/methane mixture.

Due to the fairly large number of CAEN channels (144) and to particular features of the switching on/off procedure, special software has been developed for the high voltage control. This optimizes the time needed to ramp up the chambers' high voltages and performs extensive checks on the power supply hardware to ensure safe operation of the chambers.

Since energy and position measurements depend critically on the gas mixture, continuous monitoring of the drift velocity and chamber gain is performed on external drift tubes connected to the gas system [24]. These measurements are performed using CAMAC devices, which are then read out by a G64 acting as a crate controller.

2.5.2 Forward Electromagnetic Calorimeter (EMF)

The Forward Electromagnetic Calorimeter [25] consists of 9064 lead glass blocks backed by phototriodes. All phototriode high voltages on each side are supplied by a single Kepco high voltage unit. A splitter allows the voltage and current for each quadrant to be individually controlled and monitored directly by G64, and the 2560 currents drawn by individual groups of phototriodes are also monitored. A water cooling system is employed and temperatures are monitored, allowing the detector to be automatically switched off if the temperature rises too high.

2.5.3 Hadron Calorimeter (HAC)

The iron yoke for the magnet is instrumented with plastic streamer tubes [26], which detect showers produced by hadrons interacting in the iron. Both the barrel and endcap detectors use the same principles. Tubes are packed in layers and layers form towers.

The high voltage [27] for each tower is provided by a single CAEN channel, for which automatic trip-recovery is provided. Each of the 1872 layers can be disconnected separately by relay. This prevents a single short putting an entire tower out of action. To achieve this, the current drawn by each layer is monitored [28]; if it is too high, the relay is switched off directly by the G64 (for speed). The front-end electronics supplies are also controlled [29]. Test streamer tubes are used to monitor the carbon dioxide/isobutane/argon gas mixture quality and drift velocity.

2.6 Muon Chambers

The Muon Chambers are designed to identify muons by detecting them outside most of the iron of the hadron calorimeter — all other charged particles will probably have been absorbed within the calorimeters. Three layers of drift chambers are provided for muon detection in the barrel, and two in the endcaps; the first layer is inside the outer layers of iron, and the others are on the outside.

Both Barrel and Forward Muon Chamber high voltage control includes automatic trip-recovery, similar to that described for the Forward Tracking Chambers in section 2.3 (though without the form of channel grouping used there).

2.6.1 Barrel Muon Chambers (MUB)

The Barrel Muon Chambers' [30] high voltages are applied to both the anode wires (6150 V) and the cathode (grading) strips (graded with voltage between 4000 V and ground). Hardware interlocks ensure that both anode and grading will trip if the current drawn by either is too large. The voltage difference between anode and grading is further protected by automatically ramping the voltages in 500 V steps. Special conditioning logic automatically comes into operation for sectors tripping repeatedly. This reduces, for a time, the target voltages to find a level where the chambers can operate without tripping. The voltages are ramped down if the gas supply is stopped or the argon/methane/carbon dioxide mixture is bad (in addition to the general switch-off in the event of a gas loss).

2.6.2 Forward Muon Chambers (MUF)

The Forward Muon Chambers' [31] anode wire voltages are provided by CAEN and the cathode strips by FUG power supplies, which are controlled directly by the G64s. The anode voltages are varied with atmospheric pressure in order to maintain a constant efficiency. The drift velocity is monitored [32] with a special chamber supplied with the same carbon dioxide/argon/isobutane/isopropanol gas mixture as the detector.

2.7 Scintillators

Scintillators provide a very rapid signal on the passage of charged particles, and so are an important component of the trigger to read out the rest of the detector. They can also be used to reject cosmic muons, which are not synchronized with the beam crossing. Light generated in the scintillating material is detected with photomultipliers, which require high voltage supplies.

2.7.1 Scintillator Trigger Counters (SCI)

Scintillators [33] to provide fast triggering on electromagnetic showers are placed close to the position of shower maxima in the HPC (section 2.5.1). High voltages for the photomultiplier tubes are provided by non-standard CAEN voltage dividers, controlled using the HPC G64 system and special VAX software.

2.7.2 Time of Flight Counters (TOF)

A single layer of scintillators [34, 35] is mounted just outside the Solenoid. High voltages are used for the photomultiplier tubes.

2.7.3 Forward Scintillator Hodoscope (HOF)

Scintillators just outside the endcap iron are also used to improve muon detection efficiencies. The HOF slow controls are considered a subsystem of the Forward Muon Chambers (section 2.6.2), which provides high voltages for the photomultiplier tubes.

2.8 Luminosity Monitors

Knowledge of the electron–positron luminosity is required for the measurement of cross-sections. Precise measurements of the luminosity are obtained by measuring the rate of small-angle Bhabha ($e^+e^- \rightarrow e^+e^-$ scattering) events.

The slow controls of the luminosity monitors (SAT and VSAT) are described in [36]. Bias voltages for both detector partitions are provided by special low voltage crates, which are connected via RS232–C to a shared G64.

2.8.1 Small Angle Tagger (SAT)

The Small Angle Tagger consists of a lead/scintillating fibre calorimeter [37] (read out with photodiodes) and a silicon-strip tracker [38].

2.8.2 Very Small Angle Tagger (VSAT)

The Very Small Angle Tagger [39], by virtue of the higher Bhabha rates at lower angles, allows the luminosity to be monitored online, and is used as a crosscheck of the SAT. It consists of interleaved tungsten converters and silicon detectors.

2.9 Other Systems

Monitoring is also performed for the central data acquisition and trigger system fastbus crate power supplies, temperatures at various places round the DELPHI barrel, cavern temperature and humidity, and the detector cooling water temperatures, flows, and vessel condition.

3 Front-end Systems (G64)

The lowest level of computer functionality (excepting intelligent devices such as the CAEN high voltage units described in section 3.1.3) is vested in the G64 systems. These are located in the electronics counting rooms adjacent to the detector in the experimental cavern. The number of G64s used by each detector partition is shown in table 1. In total 85 G64 crates are used: 48 for the detector monitoring and control, 33 for the gas systems,[2] and 4 for the magnet.

3.1 G64 Hardware

G64 is a simple 64-line microprocessor bus developed by the Gespac company [40], though the term is often used to designate the entire computer system. Its simplicity has led to the production of a number of cheap input/output cards, and is thus well suited to an experiment, such as DELPHI, with a requirement to monitor and control a very large number of channels, without particular emphasis on speed.

The **MAC–G64** chassis [41], designed by CERN ECP division initially for ALEPH, has also been used by DELPHI (figure 2). It contains two card frames; the lower has a G64 bus, whilst the upper is used to hold the **MAC** (monitoring and control) cards [42] which are tailored to specific input or output functions (such as multiplexing analog signals). These cards are read out using a small selection of G64 cards (typically analog-to-digital converter (ADC) and digital input/output cards) in the lower cardframe. This separation enables a small number of cards to be used for a variety of functions, simplifying the software and the maintenance of the hardware. In addition, the electrical separation of the MAC and G64 buses reduces noise problems by allowing the MAC cards to be separately grounded.

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[2] 6 of these are supervisors, which are not included in table 1.

Partition	Number of G64s		Number of SC Elementary Processes					Comments
	SC	gas	HV	LV	temp	FB	other	
VD	2	–	–	2	1	1	$1^{p)}$	
ID	1	3	$1,2^{m)}$	1	1	1	–	High voltages supplied by LeCroy units and directly controlled by VAX processes which emulate G64s/CAENs.
TPC	$7^{p)}$	3	$1^{p)}$	$2^{p)}$	$1^{p)}$	$2^{p)}$	$2^{p)}$	
OD	2	2	1	–	1	1	–	
FCA	–	2	1	–	–	1	–	FCA and FCB G64 crates are shared.
FCB	$2^{m)}$	3	$2^{m)}$	1	–	2	–	
RIB	$2,2^{m)}$, $4^{p)}$	1	$3^{m)}$	–	$2^{p)}$	$1^{m)}$	$7^{p)}$	RICH fluids are overseen by five Siemens process controllers.
RIF	$2,2^{m)}$	1	2	–	2	2	2	
HPC	$2,4^{p)}$	3	$1^{p)}$	$1^{p)}$	1	–	$2^{p)}$	
SCI	–	–	$1^{p)}$	–	–	–	–	HPC G64/CAEN crates used.
EMF	$2^{p)}$	–	$2^{p)}$	$2^{p)}$	$2^{p)}$	$2^{p)}$	–	
HAC	$5^{m)},1^{p)}$	4	8	4	–	1	–	
MUB	2	2	$2^{m)}$	2	–	2	–	
MUF	$2^{m)}$	3	$2^{m)}$	2	–	2	$2^{m)}$	
HOF	–	–	$2^{m)}$	–	–	–	–	MUF G64/CAEN crates used.
TOF	1	–	1	–	–	1	–	
SAT	$1^{m)}$	–	–	$1,1^{m)}$	1	1	–	SAT and VSAT G64 crates are shared.
VSAT	–	–	–	$1,1^{m)}$	–	1	–	
Sol	$4^{p)}$	–	–	–	–	–	$3^{p)}$	The Solenoid is described in section 9.3.
Misc	2	–	–	–	3	2	–	
Total	52	27	32	21	15	23	19	

Table 1: G64 crates and Elementary Processes used by each detector partition. The numbers of slow controls detector-monitoring (SC) and gas-system G64s are given, as well as the numbers of Elementary Processes for high voltages (HV), low voltage electronics (LV), temperature monitoring (temp), fastbus power supply monitoring (FB), and others.

$^{m)}$ indicates that the G64 Skeletons or VAX Elementary Processes (EP) have been modified (often only slightly) for functions specific to a particular detector partition.

$^{p)}$ indicates that partition-specific programs, not based on the G64 Skeleton or standard Elementary Process, are used.

Note that the gas-system G64s run a different program from the detector-monitoring G64s.

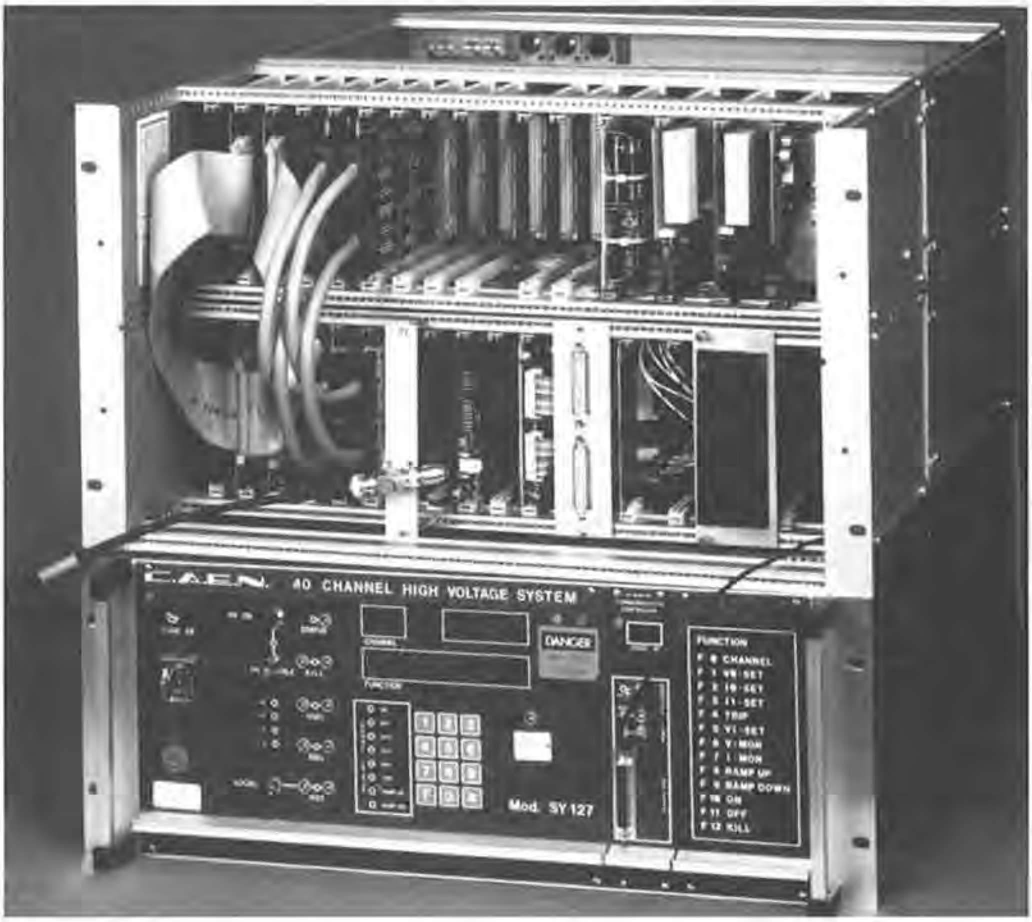


Figure 2: The MAC–G64 and CAEN crates. The MAC–G64 crate (on top) consists of a G64 bus below a MAC bus. The G64 bus contains, from left to right, a double-card CAEN interface, two digital input/output cards, a G64–ethernet interface connected to thinwire ethernet, a CPU card with two RS232–C connectors, and a disk controller and drive. The MAC bus contains a double-card CAEN interface, two digital input/output adapters, and the power supplies on the right. Below the MAC–G64 crate is a CAEN high voltage crate, connected to the G64 by CAENnet.

3.1.1 G64 cards

The G64 system was designed with the 6800-series of 8-bit microprocessors in mind. The CPU card [43] used by DELPHI includes the Motorola 6809E [44] microprocessor, 256 kilobytes of RAM, 32 kilobytes of ROM, two serial (RS232–C) interfaces, and a real-time clock. Peripherals on the G64 bus are memory-mapped, normally into a 1-kilobyte region, the **Valid Peripheral Address** space, which is decoded on the CPU card.

Since the 6809 has a 16-bit address bus, it can only directly address a maximum of 64 kilobytes. Additional memory (either RAM on the CPU card or RAM/EPROM on other G64 cards) can be addressed by using a paging facility on the CPU card, which allows, in our case, different 32-kilobyte sections of memory to be brought into use under program control.

Communications with the VAX systems is effected using a G64–ethernet interface [45]. This contains a 68000 processor, onboard RAM and EPROM, and the LANCE ethernet chip. The G64 CPU has access to a window of the 68000's RAM, and the 68000 can access all of the 6809's address space, allowing DMA transfers.

Two broad configurations of G64 cards have been used by DELPHI. 'Development' systems contain a CPU card, EPROM card containing parts of the operating system, floppy disk controller card and $3\frac{1}{2}''$ disk drive, ethernet card, and various input/output cards. Once the system is considered stable, the EPROMs are filled [46] with the application program and the floppy disk drive and controller are removed. This 'production' system can run with or without a terminal connection.

3.1.2 Input/Output cards

The main input/output G64 cards used are a Parallel Input Adapter (PIA) card for reading digital statuses, analog-to-digital converter (ADC) cards (10- and 12-bit resolution) for reading analog voltage levels, and an Output Register card to control digital states. The output register card is preferred to the PIA card for control, as all its outputs go to the same (off) state when the G64 crate is switched on or reset. Each ADC card has 16 channels; the digital input/output cards have 32.

Many of the required ranges accepted by the G64 input cards, or voltages produced by the output cards, are not suitable for direct connection to the detector. The conversion and electrical isolation is performed by the MAC cards: input adapters, relay cards, platinum resistance thermometer (PT100) temperature adapter cards, etc. Multiplexer cards, coupled with a PIA card, allow a single ADC channel to monitor 32 input voltages, albeit more slowly. The type of each MAC card can be read out by a special G64 card, allowing a crosscheck between program configuration and the actual hardware installed.

3.1.3 CAEN High Voltage Unit

Most high voltages required by DELPHI are produced by the CAEN system [2] (figure 2). Each crate can control up to 40 channels, divided into modules of 4 channels each. Different modules can be fitted for different channel characteristics, such as maximum voltage or current resolution.

The CAEN crates can be accessed by a front-panel keypad and LED display, by terminal (using a menu-driven system), or from the G64. Normal operation in DELPHI relies on the link to the G64, which is effected via a G64–CAEN interface and then CAENnet to the CAEN crate. CAENnet allows up to 100 crates to be daisy-chained together, allowing a total of 4000 channels to be controlled and monitored from a single G64–CAEN interface.

CAEN channels are normally maintained at a constant voltage (`V0`) unless the current drawn exceeds a preset limit (`I0`). In this case, the CAEN can be set either to trip (switch off) that channel immediately, or to enter a constant-current mode for a prespecified time before tripping (unless the load is reduced in the meantime). When voltages are changed, they ramp up or down at a preprogrammed rate. After the command to start ramping has been given, the CAEN is free to accept other commands for the same or different channels. All these parameters can be individually set or read (for each channel) from the G64. The channel statuses (i.e. whether on, off, tripped, etc.) and actual voltages (`VMON`) and currents (`IMON`) can also be read from the G64.

In the event of a computer failure, the operator can initiate a hardwired central rampdown of all CAEN high voltages; this ramps the CAEN to an alternate set of voltages (preset to zero in the CAEN), and subsequently triggers a 'kill'.

3.2 G64 Software

3.2.1 System Software

The G64 'operating system' is extremely primitive, and contains no facilities for multitasking.

The 4 kilobyte **monitor** program in EPROM handles the initialization, and provides basic routines for terminal and disk input and output. When the system is switched on or reset, the monitor either bootstraps the operating system from disk (in the development systems) or loads the application program from EPROM.

The FLEX disk operating system [47] allows the editing, compilation, and running of programs from disk.

Most application programs for the G64 have been written in Omegasoft Pascal [48]. As well as standard Pascal features, this compiler allows the program to be split into separate modules, and allows direct addressing of memory-mapped peripherals.

The size of the DELPHI standard application program is considerably larger than the 64-kilobyte address space can hold. A mechanism has been developed to allow different modules of a program to be placed on different pages in memory, overcoming this problem [49]. Calls between Pascal routines on different pages are made in a transparent fashion.

3.2.2 Communications

Communications between the VAX and G64 systems [50] use the OSI transport protocol over ethernet (IEEE 802.3). The protocols are handled by the Marben Osiam product [51], running in the G64–ethernet card. An interface to this, CATS/TP4 [52], has been implemented on the G64–ethernet card, using the **CATS** (common access to transport service) calling standard developed at CERN [53]. CATS attempts to standardize calling sequences to different transport protocols and implementations. A simple protocol allows CATS calls on the G64 to be executed by CATS/TP4 on the G64–ethernet card, using the shared-memory window.

Remote Procedure Calls (RPC) [54] are used both on VAX and G64 to communicate commands and data. RPC is based on a client–server model, and allows network calls (i.e. calls to CATS) to be hidden from the application. The client application calls an application-defined routine, which is implemented on the server. The RPC system takes care of transmitting the request, along with the input parameters of the call, to the server. The server RPC system then calls the requested routine with the parameters decoded from the received message, and, upon its completion, sends back the return parameters to the client RPC system, which returns them as output parameters to the client application. RPC also handles the translation between different number representations, such as the different floating point representations used by the VAX and Omegasoft Pascal on the G64.

3.2.3 Application Program (G64 Skeleton)

Most G64 systems run a standard program, the **G64 Skeleton** [55], though a few use dedicated programs (marked $^{p)}$ in the *SC G64* column of table 1).

The G64 Skeleton, being at a low level and running on a comparatively slow computer, was designed for greatest simplicity. Essentially it tries to hide from the VAX the details of accessing the hardware, providing little 'intelligent' control, while at the same time minimizing the amount of communications necessary with the VAX.

Control and inquiry functions are implemented as remote procedures callable from the VAX (i.e. RPC with VAX as client, G64 as server). For efficiency, a single remote procedure call can read or set a number of channels if desired.

The G64 Skeleton executes a continuous program loop, monitoring all input channels. Any status change is flagged by calling a reporting routine on the VAX via RPC (i.e. G64 as client, VAX as server). Again, for the sake of efficiency, if the G64 detects several status changes within one monitoring loop, up to 10 of these are buffered into a single call.

The RPC/CATS/OSI connections are initiated from the VAX and repeatedly checked with application-watchdog messages from both sides.

A simple model of the hardware is presented to the VAX: channels are classified either as digital input, digital output, analog input, analog output, or CAEN. Except for CAEN channels, all values are represented as integers at this level: `0` or `1` for digital channels, or ADC counts (e.g. `0` to `1023` for a 10-bit ADC) for analog channels. Since the CAEN communicates voltages and currents in units of the resolution of the relevant module (whose type need not be known to the VAX), the G64 Skeleton program applies appropriate scale factors so that the VAX can use volts and microamperes for all CAEN channels, regardless of their type.

Digital and analog input channels are monitored continuously. The error status of analog channels is determined using a desired value and two error limits. If the monitored value differs from the desired value by more than the first error limit, then the channel goes into error. In order for the error to be cancelled, the value must return to within the (narrower) second error limit. This hysteresis prevents frequent state changes when the value hovers around the limit. State changes in either direction (going into, or out of, error) cause a notification to be sent to the VAX.

CAEN channel statuses are monitored continuously, and any changes are reported to the VAX. While the actual voltages and currents are readable by command from the VAX, these are not continuously monitored by the G64, since any faults here will be signalled by the CAEN with a status change.

Digital *setting*, analog *setting*, and CAEN channel *settings* are only accessed by explicit initialization or changes requested from the VAX.

The channels to be monitored and their desired ranges are defined by RPC commands from the VAX. In addition, the G64 Skeleton program can be cleanly tailored for the few systems with special needs, such as those with special hardware or with a requirement for fast or particularly reliable intervention at the G64 level. (For example the Forward RICH stops TMAE flow immediately if the temperature drops below 25°C.) This allows most systems to be run from a standard EPROM, while maintaining flexibility.

4 VAX Systems

4.1 Hardware

The higher level control, overseeing, and logging is performed from various VAX systems in a single VAXcluster, located in the surface control room.

A VAX 6000 is used for the central data acquisition, a VAX 4000 for user access, and a VAXstation 4000 for the central slow controls. There are also a number of general-purpose VAXstations. In addition each major detector partition has one or two VAXstations (mostly VAXstation 4000s — 17 in all), which perform local data acquisition, monitoring, and slow controls. In this paper, the term **VAX** is used to refer to any of these systems — they are all binary-compatible.

Ethernet is used for the connections between the VAXes, and for the link to the detector G64s and front-end data acquisition crates in the cavern. However, the main (Fastbus) data flow between the cavern and the VAX 6000 on the surface goes via an optical link. An FDDI optical link is used to connect the DELPHI ethernet to the main CERN site, 7 km away.

4.2 VAX System Software

The **VMS** operating system is used. This provides multitasking, virtual memory, a networked filestore, and a rich set of system routines. From amongst them, the slow controls software has made heavy use of event flags, mailboxes, interrupts (VMS ASTs), global sections, and logical name translation services [56].

For communications with the G64s using the OSI protocols, the VOTS package was used at first. This has subsequently been merged with the native VMS networking system as DECnet Phase V. Except for the main dataflow, TCP/IP is used for communications between the VAXes and Fastbus data acquisition crates.

A variety of programming languages is used for the slow controls software. For its natural interfacing with VMS system services, and due to its familiarity to physicists, VAX/Fortran — essentially Fortran 77 with extensions such as structures — is used for the Elementary Processes, the error message display, and the databases. To allow a comparatively easy porting to the G64, we have benefitted from the implementation of the Remote Procedure Calls system in Pascal. For its interfaces to X products, and familiarity to software engineers, C is used for most of the software related to operator interaction and information exchange (HIPE, DUI, and DIM, which are described later). For its rich real-time and multithreaded capabilities, Ada is used for the Error Message Utility and the State Management Interface. While this profusion of languages has had the disadvantage of compartmentalizing expertise, the definition of clear interfaces between the various systems has meant that in practice this has produced few problems.

Traditionally ASCII terminals have been used, and many of the user-interaction programs were originally written with a user interface based upon simple VT100-style menus (using either VMS's SMG [57] or CERN's MHI [58] menu packages). More and more, however, the online programs are being converted to use the X-Windows/Motif [59, 60] graphical user interface. As well as allowing more detailed colour displays, there is no doubt that its use is more intuitively obvious for the operator. Since it can be used over the network (unlike many other graphical user interfaces), X-Windows allows experts to check up on many aspects of the detector operation without leaving the main CERN site, or even their foreign institutes. The disadvantage of this system is that it requires access to an X-terminal. For this reason many of the old ASCII-based user interfaces continue to be maintained in parallel.

5 VAX Monitoring and Control Programs

5.1 Elementary Process (EP)

G64s communicate with the Elementary Processes, which in general run in the detector partitions' VAXstations. Most Elementary Processes either use standard software or are closely based on it, and work with the G64 Skeleton program described in section 3.2.3. A few are dedicated programs (marked $^{p)}$ in the *Elementary Process* column of table 1), including those which handle the less standard applications. It is the standard program that will be described here.

Each elementary process oversees one subsystem of a detector partition, and is represented in SMI by a single object, whose state indicates the condition of that subsystem. For example, the temperatures on one side of the Hadron Calorimeter are monitored by one EP and are represented by one SMI state (indicating whether they are within an acceptable range).

The Elementary Process provides the connection between, on the one hand, the G64s and, on the other, the State Management Interface (SMI, described in more detail in section 8), the Error Message Utility (EMU, section 6), and the expert user interface (HIPE, section 5.2). It also updates the Status Update Database (section 7.2). These connections are represented diagrammatically in figure 1. In order to handle interrupts from many of these sources, as well as to perform periodic monitoring, it is by necessity event driven, using the mechanism of VMS event flags [56].

Each Elementary Process communicates with one or more G64s, and each G64 can communicate with up to eight EPs (though each channel reports its status changes only to one EP). Thus an Elementary Process can control, monitor, and accept status changes for a large number of channels. Status change reports call an RPC routine as an interrupt (VMS AST level), allowing immediate timestamping and reporting to EMU. Other actions, such as recomputing the SMI state, are queued for subsequent execution. Analog values sent or received from the G64 can have a linear transformation applied to allow for conversion from the integer ADC count to the physical parameter being measured (e.g. temperature or voltage).

Channel definitions, normal settings, and conversion factors are read from the Slow Controls Configuration Database (section 7.1). This also defines names for each channel, to make any error messages (sent via EMU) helpful to the operator. The overall program configuration is defined by VMS logical names. 'Hooks' are provided in the code to provide for special requirements (e.g. the automatic trip-recovery used by the forward tracking and muon chambers, described in section 2.3).

The Elementary Process can accept commands from, and report state changes to, SMI. At any time a single SMI state is evaluated to represent the status of all channels overseen by an Elementary Process: these states are listed in table 2. SMI commands, which act on all relevant channels, perform actions such as switching apparatus on, off, or to an intermediate (standby) level (normally only used for high voltages).

State changes in each channel, reported by the G64, are sent to EMU. These generally indicate an error condition being either raised or cancelled, though computer problems, such as communication errors, also generate EMU messages.

Changes in channel statuses reported by the G64, and in parameter values determined by periodic monitoring are written onto the Status Update Database for use by the offline data analysis. Multiple changes occurring together (within a few seconds) are combined in order to reduce the number of updates to the same database record (timestamped according to the time of receipt from the G64). Database updates are usually inhibited when no data is being taken in order to minimize the number of updates due to the raising and lowering of the high voltages at the start and end of datataking. Outstanding changes are then written (backdated to their last change) when datataking commences. These updates are sufficient because the offline programs only require the detector status at the time of the events being analysed. Since this task is of lower priority than others, a block of database updates may be temporarily interrupted, for instance to respond to an operator command.

Special procedures are included for the CAEN. When a command to change the voltages is given, all parameters (ramping rates, etc., as well as voltage values) are downloaded from the Elementary Process to the G64 and thence to the CAEN. If defined in the configuration database, a special ramping current limit is used in order to prevent trips due to the higher currents drawn during ramping. When completion of the ramp is signalled by the G64, the normal current limit is downloaded. The Elementary Process also has to recognize CAEN crate-wide conditions, such as the disabling of high voltages by manual intervention.

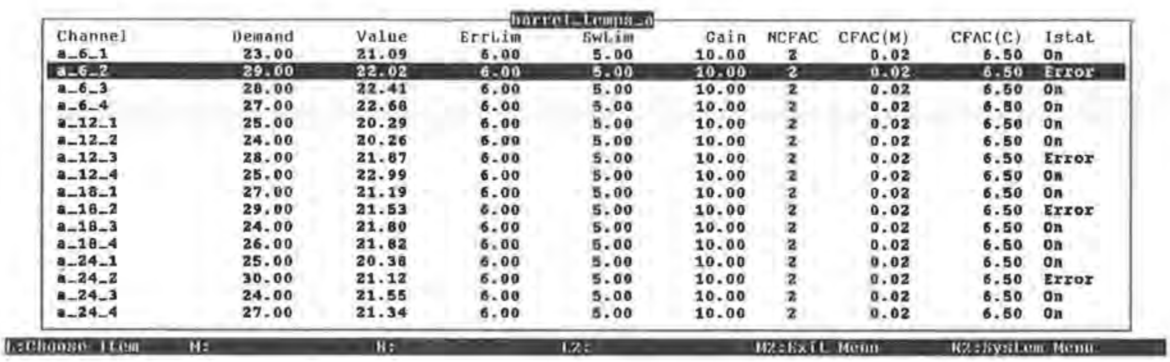
5.2 Expert Interaction (HIPE)

Display and control of individual channels by detector experts can be effected via the Elementary Process using the HIPE [61] user interface (see figure 3). This allows, for example, high voltages to be adjusted for problem channels. At a command from HIPE, these modified values can then be written by the EP to the Slow Controls Configuration Database, to become the new standard values. HIPE uses a VMS global section to retrieve information directly from the EP's datastructures in memory. This keeps interactive access from interrupting the work of the Elementary Process, though commands (such as the adjustment of channels) can be left for the Elementary Process to perform when it is free.

HIPE user interaction is based on the MHI [58] menu package. The definition of the Elementary Processes to which HIPE must connect, the channels and groupings, and the menu structure is made by configuration file. Special channel types or requirements can usually be accommodated by changing the default menu structures.

6 Error Message Handling (EMU)

The Error Message Utility (EMU) [62] is a CERN product which provides a unified system for handling alarm, error, warning, and informational messages from the slow



Channel	Demand	Value	ErrLim	SwLim	Gain	NCFAC	CFAC(M)	CFAC(C)	Istat
a_6_1	23.00	21.09	6.00	5.00	10.00	2	0.02	6.50	On
a_6_2	29.00	22.02	6.00	5.00	10.00	2	0.02	6.50	Error
a_6_3	28.00	22.41	6.00	5.00	10.00	2	0.02	6.50	On
a_6_4	27.00	22.68	6.00	5.00	10.00	2	0.02	6.50	On
a_12_1	25.00	20.29	6.00	5.00	10.00	2	0.02	6.50	On
a_12_2	24.00	20.26	6.00	5.00	10.00	2	0.02	6.50	On
a_12_3	28.00	21.87	6.00	5.00	10.00	2	0.02	6.50	Error
a_12_4	25.00	22.99	6.00	5.00	10.00	2	0.02	6.50	On
a_18_1	27.00	21.19	6.00	5.00	10.00	2	0.02	6.50	On
a_18_2	29.00	21.53	6.00	5.00	10.00	2	0.02	6.50	Error
a_18_3	24.00	21.80	6.00	5.00	10.00	2	0.02	6.50	On
a_18_4	26.00	21.82	6.00	5.00	10.00	2	0.02	6.50	On
a_24_1	25.00	20.38	6.00	5.00	10.00	2	0.02	6.50	On
a_24_2	30.00	21.12	6.00	5.00	10.00	2	0.02	6.50	Error
a_24_3	24.00	21.55	6.00	5.00	10.00	2	0.02	6.50	On
a_24_4	27.00	21.34	6.00	5.00	10.00	2	0.02	6.50	On

Figure 3: A typical screen from the HIPE Expert Display. Each row shows information for a single channel (it could also show a summary of a group of channels). In this case, some of the temperatures from the DELPHI environmental monitoring are shown. `Channel` gives the sensor name, `Demand` the nominal desired temperature, `Value` the actual monitored value, and `Istat` the channel status (e.g. whether it is in error — in this case a number of channel values are out of range, as the detector is switched off). Other monitoring parameters are also shown, and further details can be requested by selecting a channel.

controls and data acquisition systems. Messages, which can be injected anywhere on the network, are formatted by the EMU system according to a message description file. They are then sent to one of a number of logfiles or destination processes according to a message routing file.

Application programs inject messages into EMU using a short message name (e.g. `set_error` or `clr_error`) and usually some parameters (e.g. the channel name).

The EMU system consists of three processes, which in DELPHI all run on the central slow controls workstation, though in general they could each have many instances on different machines. The EMU DECnet server acts as an RPC server for the application programs, simply sending the messages without change via a mailbox to the EMU Decoder.

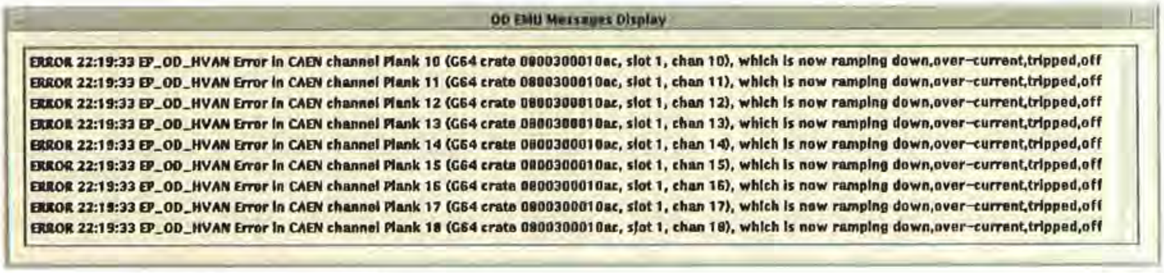
The Decoder attaches a **description** and **properties** to the message according to those listed in the message file for the given message name. The description will be used in the logfile and EMU display to clarify the message. The parameters sent by the application program are inserted at appropriate points to make an 'English' sentence. The properties are used for routing the message, and for selections by the EMU display (see section 6.2).

The Decoder passes the message on to the EMU Router, which decides where to send the message: into one of a number of logfiles, or on to an application process. The routing can be based upon the name, properties (as attached by the decoder), or source of the message, as specified by logical expressions given in the routing file for each destination.

6.1 Use of EMU in DELPHI

Each Elementary Process or data acquisition program injects messages into EMU. The standard EPs use a limited set of message names (and hence they all can be associated with a single message description file). The message parameters are used to send specific information such as the channel name or the newly-read value.

In order to allow the EMU display to match an error message with its cancellation, an additional convention is observed [63]. The message names start with `set` (for raising) or `clr` (for cancelling messages), and significant text (such as the channel name, which clearly must be the same if the two messages are to refer to the same condition) is enclosed in square brackets. If these, the injecting program, and some additional properties match, then the EMU display is able to remove the message from the list of outstanding errors when the cancellation message is received.



```
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 10 (G64 crate 0800300010ac, slot 1, chan 10), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 11 (G64 crate 0800300010ac, slot 1, chan 11), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 12 (G64 crate 0800300010ac, slot 1, chan 12), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 13 (G64 crate 0800300010ac, slot 1, chan 13), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 14 (G64 crate 0800300010ac, slot 1, chan 14), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 15 (G64 crate 0800300010ac, slot 1, chan 15), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 16 (G64 crate 0800300010ac, slot 1, chan 16), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 17 (G64 crate 0800300010ac, slot 1, chan 17), which is now ramping down,over-current,tripped,off
ERROR 22:19:33 EP_OD_HVAN Error in CAEN channel Plank 18 (G64 crate 0800300010ac, slot 1, chan 18), which is now ramping down,over-current,tripped,off
```

Figure 4: A typical screen from the EMU Display. On the left are the controls, with a button to select each partition's messages. Those that have unseen messages are coloured according to the highest severity of message. Above the controls are the messages for the Outer Detector (selected by clicking on the `OD` button). These show a number of trips of CAEN high voltage channels.

Each detector partition (or other system, such as the central gas system) has one EMU logfile, which is normally only of interest to detector experts. All messages from that partition, or messages relevant to that partition from the gas or safety system, are sent to this logfile. Warning, error, and alarm messages are also sent into central logfiles (one for the slow controls and one for the data acquisition), which are watched by dedicated EMU displays on the operators' workstations. New versions of the logfiles are created every midnight, while the old versions are kept available for inspection by detector experts.

EMU messages corresponding to conditions that require rapid intervention from a detector expert are routed to a 'beep-caller' program. This uses the auto-dial facility of a modem to dial the telephone number that activates the pager carried by the appropriate detector expert.

6.2 EMU Display

The EMU Display [64] is a general configurable utility for showing outstanding conditions reported by EMU. It is based on the X-Windows/Motif graphical user interface (figure 4), though a VT100-style terminal interface based on MHI is also provided.

The program watches for updates that EMU makes to a logfile (signalled by the VMS file system) and displays them according to category (e.g. by detector partition or severity), which may be selected for display separately. If not currently displayed, a new message is indicated by a colour change (according to its severity) on the button corresponding to its category. Cancelled messages are removed from the display, though they remain in the logfile. A logfile browsing facility is also provided.

In normal operation EMU displays are used by both data acquisition and slow controls operators to monitor warning, error, and alarm conditions.

The program is highly configurable (both by configuration file and interactively), allowing it also to be useful for detector experts to monitor or browse the partition-specific logfiles.

7 Databases

The DELPHI databases are based on the CARGO [65] hierarchical database system, which in turn uses a modified version of CERN's KAPACK [66] keyed-access file management routines.

CARGO provides facilities for creating, updating, and interrogating the database, either interactively or from a program. Its special features are the timestamping of updates to a record, and the ability to create a formatted **ASCII file.** Each update has a **period of validity,** which is usually from the time of the update until the next update. This allows an analysis program to read the data item that was valid at any past time, such as at the time that a particular physics event was recorded. The ASCII file contains a representation of all of, or a selected subset of, the binary database file. This is particularly convenient for the periodic transport of database updates from the online to the offline computers, which also use CARGO to store the detector calibration and alignment.

Each of the main CARGO databases used in the online system (slow controls configuration, slow controls status update, and LEP machine parameters) has an **access package,** which provides a set of routines through which all database accesses are performed. Application programs can either call these routines directly to access a private database file, or can make a remote procedure call to a database server process to access the common database files. The use of RPC provides automatic protection against conflicts, such as two programs attempting to write to the same record at the same time, since the server executes only one command at a time. It also greatly simplifies the task of coordinating the export of update ASCII files to the offline computers, since all updates go through the same process.

7.1 Slow Controls Configuration Database

The Slow Controls Configuration Database [67] lists characteristics, physical addresses, default values and error limits for each channel associated with an Elementary Process. It also defines the correspondence between G64 channel number and the Status Update Database word or words where changes will be recorded, and the tolerance on the readings before an update is made.

Since updates to this database are only made at experts' request (normally only when the detector hardware or default running values are changed, e.g. via HIPE), it is usually found to be more convenient for each detector partition to have an individual database file.

7.2 Status Update Database

The Status Update Database is used by the offline analysis to determine the state of the different parts of DELPHI as each physics event is analysed. The granularity of description depends on the detector partition concerned (see [35] for an example).

Updates are written by the Elementary Processes using the database server, called via RPC. These updates are periodically exported to the offline computers. During datataking, the frequency of updates from each detector partition is checked online using time-development plots integrated into the quality checking system.

8 High-level Representation (SMI)

The State Management Interface (SMI) [68] describes the various subsystems of the experiment in terms of a set of **objects.**

Each object has a predefined set of **states** in which it can be, and for each state a set of allowable **actions** that can be requested of it. The state of each object is determined either by the state of other objects or, for **elementary objects,** by the state set in its associated Elementary Process. Similarly, actions requested of an object are either passed on to other objects or to an Elementary Process.

(a) SMI state	Condition
`OFF`	All channels are off.
`ON`	All are on and OK.
`STANDBY`	All CAEN channels are at their intermediate level.
`CHANGING`	At least one channel is ramping up or down.
`ERROR`	At least one channel is in error (e.g. reading outside limits).
`NO_CONTROL`	No communications with the G64.
`DEAD`	The Elementary Process is not running.

(b) SMI command	Action
`START`	Default settings from the Slow Controls Configuration Database are downloaded to the G64, and control channels are switched on.
`STANDBY`	Equivalent to `START` but sets intermediate values.
`REPAIR`	Equivalent to `START` but only for CAEN channels that have tripped.
`STOP`	Control channels are switched off.

Table 2: Some of the main SMI states (a) and commands (b) of the standard Elementary Process. These correspond to the states and commands of the associated object in the detector partition's SMI domain.

The definition of possible states, allowed actions, and the relationship between objects is made in a dedicated SMI language. In non-elementary objects it allows conditions to be specified which will result in an automatic state change or set of actions. For example, the state of a higher-level object can be determined by the states of lower-level objects, or commands can be issued when a state change occurs.

A group of related SMI objects forms an **SMI domain**, which is implemented in a single process. Communication between an SMI domain and other domains, or with the Elementary Processes or the user interfaces, is effected using the **DELPHI Information Management (DIM)** [69] system. This system allows SMI states to be directly viewable by the DELPHI User Interface (see section 8.2). It replaces SMI's native communication system [70], providing greater reliability, since it does not require all states to be held by a central server.

8.1 Use of SMI in DELPHI

SMI provides the primary high-level control and reporting mechanism for both the slow controls and data acquisition systems. Each detector partition is mapped onto an SMI domain, which contains an object for each Elementary Process, which oversees a single well-defined subsystem. Some of the possible states of these objects and the actions that can be performed on them are listed in table 2. The states of all Elementary Objects in an SMI domain are combined into summary objects `SC` and, where relevant, `LEP_RELATED`.

The `SC` object gives the detector partition's overall status. Its states are summarized in table 3a.

Since LEP activity (such as injection or coarse tuning) can produce a significant number of stray particles in the detector, it is advisable to reduce the high voltages of the more sensitive partitions during this time. The `LEP_RELATED` object shows the state of these high voltages, and can be used to ensure that they are all lowered before giving LEP the go-ahead for the operation.

Conditions in the ancillary gas and GSS systems (see section 9) relevant to each detector partition are relayed to that partition's SMI domain and can be used to switch off voltages when a serious condition is indicated. They can also contribute to the partition's `SC` summary state, giving the possibility of an `ALARM` state.

The summary states for each detector partition are relayed to a central SMI domain,

(a) SMI state	Condition
`READY`	Everything is on and can take data.
`NOT_READY`	One or more subsystems is not ready to take data (e.g. at standby level).
`ALARM`	Unsafe condition (e.g. gas leak).
`ERROR`	One or more Elementary Objects is in `ERROR`.
`CHANGING`	High voltages are ramping up or down.
`NO_CONTROL`	No communications with one or more G64s.
`EP_DEAD`	One or more Elementary Processes are not running.
`DEAD`	SMI domain is not running.

(b) SMI command	Action
`Prepare_For_Run`	All subsystems are `START`ed to prepare for datataking.
`Respond_To_Background`	Lowers the voltages of subsystems which are sensitive to 'dirty' beam conditions.
`Prepare_For_Injection`	Lowers the voltages of subsystems which are sensitive to the beam conditions which occur during LEP injection.
`Prepare_For_Shutdown`	Switches off all subsystems.
`Set_Central`	Switches the detector partition to central operator control.
`Set_Local`	Switches to local control.

Table 3: The main SMI states (a) and commands (b) of a typical detector partition summary object (`SC`).

which composes overall `SC` and `LEP_RELATED` summary states for DELPHI.

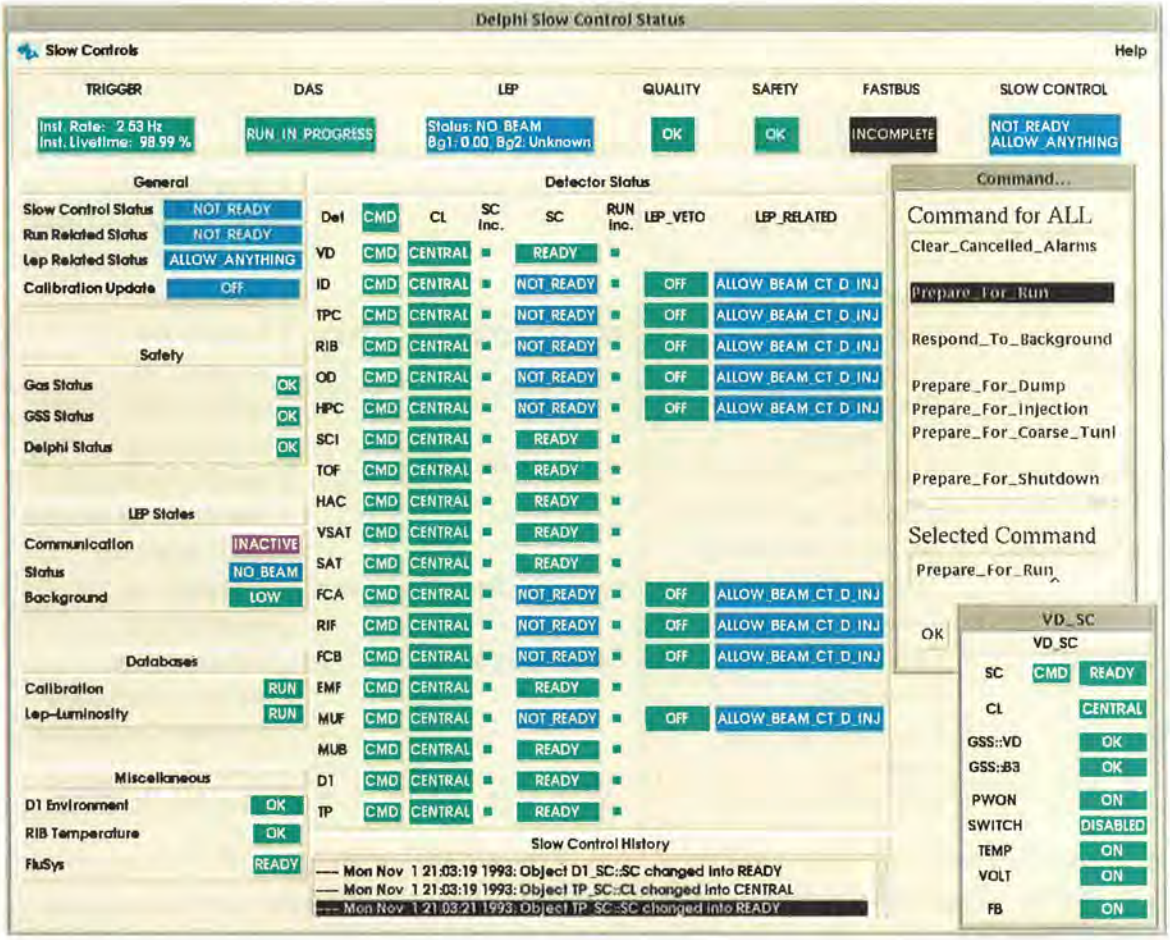
The main commands used for the control of each detector partition are summarized in table 3b. These commands can be received by the partition from one of two sources: during data taking, they normally come from the central operator via the central SMI domain; during setting up, they (and other commands designed for the control of specific detector partitions) are issued by detector experts from a local SMI display. A switch from local to central control and vice versa is provided so that central switch-on commands can be inhibited during the intervention of detector experts.

8.2 SMI Display

Operator display and control is provided by the DELPHI user interface (DUI) [71] to SMI. DUI is a general-purpose X-Windows/Motif graphical user interface. It is used to show information as varied as the slow controls statuses and the LEP collimator positions. DUI interfaces naturally to SMI due to the latter's use of the DIM system.

The SMI display program may be used to inspect and, when necessary, issue commands to individual detector partitions by local operators, or to the whole of DELPHI by the central operator.

The central slow controls SMI display, shown in figure 5, allows the operator to see the summary states of the central SMI, of each of the detector partitions, and of various ancillary systems. Details of the component states of each partition or ancillary system can also be presented from this display; an example is also shown in figure 5. The display can be used to send commands to all or part of DELPHI, or (where authorized) to an individual object within a detector partition. The available global commands are similar to those for



TRIGGER	DAS	LEP	QUALITY	SAFETY	FASTBUS	SLOW CONTROL
Inst. Rate: 2.53 Hz Inst. Livetime: 98.99 %	RUN_IN_PROGRESS	Status: NO_BEAM Bg1: 0.00, Bg2: Unknown	OK	OK	INCOMPLETE	NOT_READY ALLOW_ANYTHING

General

Slow Control Status	NOT_READY
Run Related Status	NOT_READY
Lep Related Status	ALLOW_ANYTHING
Calibration Update	OFF

Safety

Gas Status	OK
GSS Status	OK
Delphi Status	OK

LEP States

Communication	INACTIVE
Status	NO_BEAM
Background	LOW

Databases

Calibration	RUN
Lep-Luminosity	RUN

Miscellaneous

D1 Environment	OK
RIB Temperature	OK
FluSys	READY

Detector Status

Det	CMD	CL	SC Inc.	SC	RUN Inc.	LEP_VETO	LEP_RELATED
VD	CMD	CENTRAL	■	READY	■		
ID	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
TPC	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
RIB	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
OD	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
HPC	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
SCI	CMD	CENTRAL	■	READY	■		
TOF	CMD	CENTRAL	■	READY	■		
HAC	CMD	CENTRAL	■	READY	■		
VSAT	CMD	CENTRAL	■	READY	■		
SAT	CMD	CENTRAL	■	READY	■		
FCA	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
RIF	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
FCB	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
EMF	CMD	CENTRAL	■	READY	■		
MUF	CMD	CENTRAL	■	NOT_READY	■	OFF	ALLOW_BEAM_CT_D_INJ
MUB	CMD	CENTRAL	■	READY	■		
D1	CMD	CENTRAL	■	READY	■		
TP	CMD	CENTRAL	■	READY	■		

Slow Control History

```
— Mon Nov  1 21:03:19 1993: Object D1_SC::SC changed into READY
— Mon Nov  1 21:03:19 1993: Object TP_SC::CL changed into CENTRAL
--- Mon Nov  1 21:03:21 1993: Object TP_SC::SC changed into READY
```

Command for ALL

- Clear_Cancelled_Alarms
- Prepare_For_Run
- Respond_To_Background
- Prepare_For_Dump
- Prepare_For_Injection
- Prepare_For_Coarse_Tuni
- Prepare_For_Shutdown

Selected Command

Prepare_For_Run

VD_SC

SC	CMD	READY
CL		CENTRAL
GSS::VD		OK
GSS::B3		OK
PWON		ON
SWITCH		DISABLED
TEMP		ON
VOLT		ON
FB		ON

Figure 5: A typical screen from the SMI display. The LEP-sensitive high voltages are currently lowered (hence the states indicating that any LEP activity (beam coarse tuning, dump, or injection) is permitted). The local SMI for the Vertex Detector (VD), obtained by selecting the `VD SC` button, is shown at the bottom right. The command menu for all detector partitions, obtained by selecting the top `CMD` button, is shown above it with the `Prepare_For_Run` command (see table 3b) selected. On a colour screen the different states are highlighted by different colours.

an individual detector partition (table 3b); an example menu is also shown in figure 5.

A help facility is also available from the display to give advice to the operator on the diagnosis and cure of problems occurring in each detector partition.

9 Ancillary Systems

The system described in sections 3–8 oversees and controls technical aspects of the detector and its readout electronics. However, it does not operate alone. The gas supplies, environmental monitoring for unsafe conditions (GSS), the solenoidal magnet, and the LEP machine have been developed independently of the detector slow controls system. In order to allow the slow controls operator easy access to the condition of these systems, and to allow automatic actions in serious situations, these systems have been interfaced with the DELPHI slow controls at the EMU (see section 6) and SMI (section 8) levels.

The gas and Solenoid control systems were developed within the DELPHI collaboration and both use a combination of G64 and VAX computers. However, in contrast to the detector control described in section 3.2.3, much more intelligence is vested in the G64s, while the VAX is used only for user interaction, logging, and interfacing with other systems.

This has the advantage of allowing each system to operate independently. This was necessary as these systems were required before the rest of the detector controls were needed or implemented, and in any case could be run outside normal datataking periods when the other systems may be subject to frequent downtime. It did, however, lead to comparatively inflexible systems as program development on the G64 is painful, and (even using paged RAM) the program size is limited. Despite the different design philosophies, both these systems use the same G64 system software (FLEX, Pascal, etc.), the G64–ethernet card for communication with the OSI protocols, and (for the Solenoid) the RPC protocols.

The environmental surveillance and LEP monitoring systems were developed by independent groups at CERN and, like the gas and Solenoid monitoring, were interfaced *a posteriori* with the detector slow controls.

9.1 Gas Systems

All detector gases are provided by an integrated system of supplies, mixers, distributors, and purifiers [5], the state of which is monitored and controlled by 27 G64 systems. A further 6 G64s, which act as supervisors, are equipped with graphical displays and can control equipment and show the results of measurements throughout the system. The flow rates and compositions are carefully monitored, as anomalies could indicate a gas loss or a dangerous mixture.

Serious conditions are reported to a server on the VAX, which can set an `ALARM` SMI state for the parts of the detector affected, and injects an EMU message describing the problem for the operator. The `ALARM` state causes detector high voltages to be ramped down. This provides a backup to the hardwired connection directly from the gas system to the CAEN high voltage units.

An RPC server on the VAX is used to translate requests for information into commands for the gas system G64s. This facility is used to log the main gas parameters (as well as the atmospheric pressure) to the Status Update database. It is also used by certain detector partitions which base their high voltage control on the values of these parameters.

9.2 General Surveillance System (GSS)

The safe environment of all four LEP experiments is monitored independently by the General Surveillance System [6]. It monitors the ventilation, cooling water, temperatures, and flammable gas and smoke detectors. If problems are detected, it can alert the operator or the fire brigade; it can switch off gas supplies, high voltages, or mains power; and it can activate fire extinguishers. A graphical interface to GSS is provided.

The DELPHI slow controls system is linked to GSS by both hardwired signals and computer messages. Hardwired signals are generated in the case of many serious conditions and are used to switch off high voltage and other potentially hazardous equipment independently of any decision made by the software systems. Conditions detected by GSS that are relevant to DELPHI are sent to a server process on the DELPHI VAXcluster, which translates them into EMU messages and maintains the state of SMI objects for each detector partition and electronics barrack. The SMI state changes can provoke automatic actions such as switching off high voltages, before the condition becomes serious enough to force a hardwired switch-off from GSS.

Hazardous conditions detected within DELPHI, such as a gas loss detected by the gas system, are forwarded from EMU to GSS. This allows GSS to take independent action, such as performing a hardwired switch-off of gas supplies and high voltages before the possibility of a buildup of flammable gas in the environment.

9.3 Solenoidal Magnet

The solenoidal magnet [72] produces a field of 1.2 tesla by using a superconducting coil carrying a current of 5000 A, maintained at a temperature of 4.5 K. Monitoring is required for the temperature, pressure in the cryostat, current, mechanical strain, and magnetic field in a number of places round the coil. Detailed computer control of the power supplies is required.

These functions are performed by four G64 systems: for the power supplies, vacuum systems, data logging, and NMR magnetic field measurement. A standalone VAXstation 4000–VLC provides user interfaces and logs the time-variation of monitored values onto an independent database (implemented with CARGO; see section 7).

Anomalous conditions detected by the G64 systems are sent to an alarm server on the VAX. A few of these conditions, for example a severe fault in the cooling system, can provoke automatic action, such as running down the magnet currents. All messages are injected into a local EMU system, which can forward the more serious to the main cluster, thus notifying the slow controls operator in the usual manner.

9.4 LEP Accelerator

A typical LEP fill can last up to 24 hours, though background problems seen in the detectors may require intervention. During filling and high background conditions, when large numbers of stray particles can be thrown into DELPHI, the high voltages must be lowered for the Inner Detector, TPC, Outer Detector, forward tracking chambers (FCA, FCB), Barrel and Forward RICHes (RIB, RIF), barrel electromagnetic calorimeter (HPC), and Forward Muon Chambers (MUF).

The LEP machine provides information [73] on its state, and in principle could use information on DELPHI's state to constrain its actions. At the moment all these interactions are made by hand, with the slow controls operator lowering the high voltages when indicated by LEP conditions or planned actions, and informing the LEP operators of the state of DELPHI's high voltages.

10 Operations

DELPHI is normally operated by three people, concerned, respectively, with the data acquisition, data quality, and slow controls. In addition to controlling the detector, the slow controls operator has official responsibility for the safety of the detector and personnel during her shift (functioning as shift leader in matters of safety, or **SLIMOS**), and performs periodic tours round the cavern and gas barracks. Continuous SLIMOS cover is required whenever flammable gases are present in the detector, even if LEP is not running at the time. The user interfaces available in the control room are the SMI, EMU, GSS, and gas supervisor displays.

10.1 Normal Operations

The SMI display (shown in figure 5) gives the primary indication of the state of each detector partition, allowing the operator to coordinate with LEP conditions.

At the start of a LEP fill, when beams are injected into the machine, the operator must ensure that high voltages of sensitive detector partitions are lowered (normally to their standby levels). This is indicated for each partition (and DELPHI as a whole) by the `LEP_RELATED` objects shown on the SMI display. When LEP declares 'physics' conditions (colliding beams with collimators closed to reduce background), the voltages must be raised in order to allow the detector to take data. When all the voltages have reached their required levels, the run may be started. This is indicated for each detector partition (and DELPHI as a whole) by the `SC` objects showing `READY`.

10.2 Dealing with Problems

Problems shown on the SMI display may be followed up using the help facility provided there (see section 8.2) and using more detailed information from EMU (figure 4) or

HIPE (figure 3). These are typically detector equipment problems (e.g. high voltage channels tripping, which can often be cured by ramping up again), or safety-related problems reported by GSS or the gas system.

Safety-related conditions are indicated on the GSS or gas supervisor displays, as well as on the EMU display, and in addition alert the operator by telephone pager. Many alarm conditions provoke automatic actions, initially by software in a controlled manner via SMI (and hence also shown on the SMI display), and then, in the case of severe alarms, by hardwired actions such as turning off gas supplies or high voltages, or by cutting the power to part or all of DELPHI. Some of the less critical actions may be modified by the slow controls operator acknowledging the alarm.

11 Example

By way of an illustration of how the system works, we consider the operations performed over one LEP fill. This exemplifies all the components shown in figure 1 and their interrelations.

1. While particles are injected into the LEP ring, accelerated to 45 GeV per beam, and the beams are adjusted for collisions, the high voltages of sensitive detector partitions (ID, TPC, RIB, OD, HPC, FCA, RIF, FCB, and MUF) must remain lowered. Figure 5 shows the SMI display in this state. Once the collimators are closed, reducing the number of stray particles in the detector, and physics conditions are declared, the high voltages have to be raised in order to take data. This is only done if the background measured by DELPHI is acceptable; if it is not, the LEP operators are encouraged to improve the beam conditions.
2. The slow controls operator issues the global `Prepare_For_Run` command from the SMI display. This command is forwarded to each detector partition's SMI domain, but will only affect those partitions not already on (normally just those which were lowered for LEP setup) and under central control. Their Elementary Processes will be given the `START` SMI command.
3. This causes the EP to download the default running values to its G64s. For the high voltage EPs, the new voltages relayed by the G64s to the CAENs cause the channels to start ramping. This new state is detected by the G64, which reports it to the EP, which, in turn, reports its state to SMI as `CHANGING`.
4. This state is visible to the operator until all voltages for that detector partition reach their final values. Note that during this time, the EPs, G64s, and CAENs are not blocked, and can respond to other commands (for example to ramp down again if LEP has problems). As each CAEN channel reaches its final value, the new state is detected by the G64's monitoring loop, and reported to the EP. When all channels have come up, the EP sets the state of its associated SMI object to `ON`, and the detector partition's SMI becomes `READY`. When all partitions are ready, the central SMI shows `READY` and the data acquisition running may be started in order to collect data.

During this run, we now imagine a trip of a single CAEN high voltage channel.

5. The anode high voltage for plank 10 of the Outer Detector (OD), normally held at 4400 V, is detected by the CAEN to be drawing more than the specified maximum current (50 μA; normally it might be expected to be drawing 15 μA), so the channel trips.
6. When the G64 next monitors this channel (normally within 10 seconds) by reading its status byte, it will notice the change. This prompts it to make a remote procedure call to the reporting routine in the Elementary Process defined for this channel.
7. This EP immediately sends an EMU message, `set_error`, with parameters giving the channel type ('`CAEN`'), channel name ('`Plank 10`'), physical address ('`G64 crate 0800300010ac, slot 1, chan 10`'), and current state ('`ramping down, over-current,`

`tripped, off`'), which is formatted into a readable message like those shown in figure 4, and is sent to a partition-specific logfile and to the slow controls operator's EMU display.

8. The Elementary Process marks this channel as being in error. If the number of channels now in error passes a (partition-dependent) threshold, then the EP changes its associated SMI state to `ERROR`.
9. The change in the state of the high voltage object in the OD's SMI domain causes the detector partition's summary state (`SC`) to go into state `ERROR`, and the DELPHI summary state changes to `NOT_READY`.
10. The change can also result in an update of the Status Update Database. The details of the update depend upon the specifications for the specific subsystem.
11. The lack of voltage on Plank 10 will produce a reduction to zero in the efficiency of this part of the Outer Detector. If the problem were to go uncorrected for long enough, this would become statistically significant and be noticed by the data quality checker. Normally, however, the slow controls operator will see the trip on the SMI and EMU displays long before this occurs. The problem could be due to an increase in LEP background (in which case many high voltages throughout DELPHI will probably have tripped) or a momentary spike in detector background. Once the operator judges that it is safe to try to raise the voltage again, the SMI command `REPAIR` can be given from the central SMI display.
12. The `REPAIR` command is relayed via the Outer Detector SMI control object (`SC`) to the EP controlling the Outer Detector high voltage, which sends a command to the routine in the G64 for setting CAEN values. The channel starts ramping up. This change of status is reported back to the Elementary Process, which sets the SMI state to `CHANGING`. This change is reflected in the central SMI domain.
13. When the channel reaches its desired final voltage, that condition is reported to the EP, which generates an EMU message, `clr_error`, cancelling the initial report of the trip, and resets the SMI state to `ON`.

When finally the LEP beam currents are too low to give sufficient luminosity to make continued running worthwhile, LEP will dump the beam, and the data acquisition run will be stopped.

14. Before filling starts again, the high voltages of the sensitive detector partitions must be lowered to their standby levels in an analogous manner to their raising at the start of the fill. This is done with the `Prepare_For_Injection` command.

12 Experience

12.1 Particular Strengths of the System

Many advantages have stemmed from the design of the system in a highly modular fashion, with different subsystems on different platforms or in different processes, and with well-defined interfaces between them.

This modular construction renders the overall system robust against problems in any one area, so that a crash of a G64, an Elementary Process, or an SMI domain only affects those systems which it oversees. The levels above make the problem visible to the operator, allowing for a more rapid cure.

Modularity has allowed a general system to be designed and implemented for many different detector partitions, while still allowing certain parts of the system to be tailored to specific requirements with comparative ease. As we have seen, these modifications can be made at all levels: at the G64 level to cater for special hardware or for rapid reaction to specific changes; at the Elementary Process level to allow for special handling of the hardware, or to alter the determination of SMI states, EMU messages, or status updates to the database; and at the SMI level to allow for different actions during different phases of running and to amalgamate the states of detector partitions' subsystems in different ways.

Except for SMI, for which the SMI-language description for each detector partition has to be tailored for different sets of subsystems, the standard programs have proved sufficient for the majority of subsystems. This is due to the high level of configurability of most of the software.

As described in section 9, the modularity has also simplified the interfacing of the detector slow controls with the ancillary gas, GSS, Solenoid, and LEP systems.

The provision of such a modular system has been closely influenced and significantly helped by the adoption of the RPC communications and the SMI state-machine models (sections 3.2.2 and 8 respectively).

12.2 Problems and Solutions

The implementation of the system in the 'dirty' environment of DELPHI as compared to the development laboratory has resulted in previously underestimated difficulties due, for example, to problems with the heavily-loaded ethernet. In such circumstances, the importance of fast error recovery, robust programs that do not hang or crash if cooperating processes crash or restart, and good procedures for reconnecting them, becomes paramount.

A general problem of all monitoring systems is limiting spurious (and sometimes 'flooding') messages without ignoring important conditions. At various times, DELPHI has had particular problems with too frequent EMU messages or status updates to the database. When extreme, these can block the server processes against more important messages, and fill up the disks. No specific solution has yet been developed to suppress repetitive error messages for the slow controls, where a single problem can result in many error messages for all the affected channels. In these cases it would be preferable if all were combined into a single message. The database status update floods, which can also slow down the subsequent analysis programs, have been solved by allowing for the inhibition of updates when not taking data — the period when such updates are by far the most frequent and are in any case not required. Due to this change, and improvements in the efficiency of both the EMU and database servers, floods of both types are now rarely a problem.

A related problem is how to deal cleanly with known problems that have been determined to be not serious, such as a faulty sensor. Obviously the long-term solution is to fix the underlying problem, but it is not always practicable to do this immediately. Detector channels can be disabled with HIPE (short-term) or within the slow controls configuration database (long-term); gas alarms can be inhibited; and GSS alarms acknowledged or inhibited. These temporary work-arounds require careful documentation and communication between detector experts and the operators, and can thus be subject to human error.

Since DELPHI was designed to operate over a period of more than ten years, it is important to maintain a base of expertise and supplies of spare equipment to last the lifetime of the experiment. This highlights the importance of choosing widely-used hardware and software, ensuring that support for these is maintained, and of documenting carefully systems produced within the collaboration.

12.3 Re-evaluation of Past Decisions and Possible Future Improvements

The near-inevitable consequence of working in a large collaboration of independent groups is that complete standardization does not always occur, even where this is technically possible. As described above, the system has been designed to minimize the impact of this fact of life. However, the long-term ease of maintenance, in particular, would be improved by reducing the number of such special systems to a minimum. In software, this can often be done by generalizing the standard software to handle these specific cases in a configurable way. In hardware, where originally reductions in cost favoured the adoption of a solution tailored to a particular part of the detector, it is often desirable to replace these systems with more standardized ones when funds become available.

The G64 system was widely adopted at CERN and elsewhere to provide monitoring and control of a large number of disparate channels at low cost. The G64–MAC systems remain cost-effective, but the 6809 8-bit processors originally chosen for the system — although physically robust — are now to be regarded as archaic, and any similar slow controls system designed now would certainly use the 68000 family of 16-bit processors (for which CPU cards are available for G64, e.g. [74]).

13 Summary

The DELPHI slow controls system has been in operation since the LEP pilot run in August of 1989, though the system has been improved significantly since then, culminating in the system described in this paper.[3] Over this time, as higher and higher level systems have been added, the slow controls system has taken over the functions previously performed manually by detector experts. Along with analogous improvements in the data acquisition system, this has reduced the number of people required on shift from around twenty to three, allowing detector experts more time to spend on physics analysis.

By the end of 1993, DELPHI had recorded the results of about two million Z^0-decays, as well as Bhabha events used to measure the luminosity. The automation of the slow controls system (particularly the reduction in high-voltage ramping times at the start and end of LEP fills) has made a significant contribution to improving the efficiency (live-time) of datataking, which in 1993 reached an average of 90% over 1500 hours datataking.

We hope that our description of the structure and software tools of the system, and in particular our experiences presented in section 12, will be of help to physicists and engineers designing the slow controls systems (for example [75]) of future large high-energy physics experiments.

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