The KLOE Computing Environment

The KLOE Collaboration
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***Abstract*— The KLOE experiment at DAΦNE is largely devoted to the study of discrete symmetries in the $K_S K_L$ system. During 2001–2002, KLOE collected 1.4×10^9 ϕ decays, for a total data volume of nearly 200 TB. We describe the KLOE computing environment, outlining our solutions to issues of calibration, reconstruction, data reduction, and data access for analysis. We discuss the performance of the system, with particular emphasis on the data-processing and transfer rates, and also describe the generation of large Monte Carlo samples. The KLOE computing environment has been been demonstrated to be flexible and scalable in the presence of rapidly evolving data-taking conditions.**

***Index Terms*— high-energy physics experiments, computing.**

I. Introduction

KLOE is a large, general-purpose detector permanently installed at DAΦNE, the Frascati ϕ factory, an e^+e^- machine with $W \approx m_\phi \approx 1.02$ GeV. KLOE is optimized for the study of discrete symmetries in the neutral-kaon system, but the physics program of the experiment includes studies of charged-kaon decays, radiative decays of the ϕ meson, η decays, and the measurement of the cross section for $e^+e^- \rightarrow$ hadrons below 1 GeV. The DAΦNE design luminosity is 5×10^{32} cm^{-2} s^{-1}, which corresponds to a ϕ-production rate of 1.7 kHz. Given the breadth of the KLOE physics program, all ϕ decays are interesting, and as much of this rate as possible must be acquired and reconstructed.

The KLOE detector consists essentially of a large drift chamber (DC) surrounded by an electromagnetic calorimeter (EmC). The drift chamber [1] is strung with 12582 stereo sense wires. Each sense wire provides a TDC measurement; in addition, there is one ADC measurement for each group of 12 wires. The lead/scintillating-fiber calorimeter [2] consists of a barrel and two endcaps. The modules are read out on both sides by a total of 4880 PMT's, each of which provides a TDC and an ADC measurement. In total, there are about 23000 FEE channels. The readout system is discussed in detail in Ref. [3].

To complete its physics program, KLOE needs to collect at least a few fb^{-1} of data. KLOE took its first events in 1999, but significant DAΦNE luminosities were first achieved in 2001. During 2002 data taking, the maximum DAΦNE luminosity was 7.5×10^{31} cm^{-2} s^{-1}. Although this is lower than the design value, the performance of the machine during 2002 was much improved with respect to previous years, and the KLOE experiment was able to collect as much as 4.2 pb^{-1} per day. The combined KLOE 2001–2002 data set amounts to about 450 pb^{-1}, or 1.4×10^9 ϕ decays. This data set is characterized by a signal-to-background ratio that varies significantly as a function of time.

A series of recent upgrades to the machine, including an overhaul of the interaction region inside the KLOE detector, is expected to bring the design luminosity to within reach. Data taking with KLOE is scheduled to restart by early 2004. We expect to collect a data set of about 2 fb^{-1} during the upcoming running period.

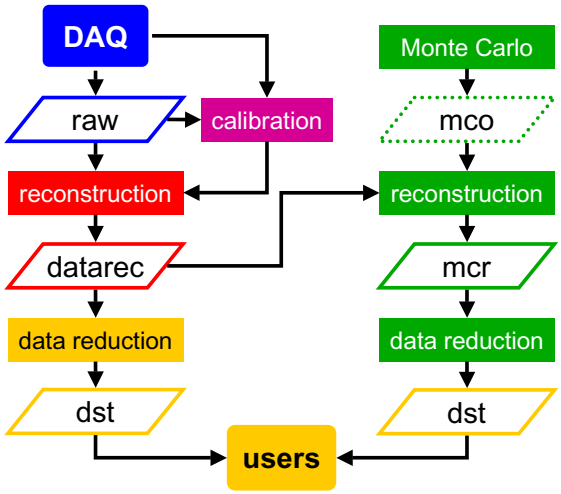

Fig. 1. KLOE data flow

II. Data Flow

A good starting point for the discussion of KLOE computing is the data-flow diagram presented in Fig. 1.

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Raw data is readout from the detector by the data-acquisition (DAQ) system and formatted and written to raw-data files by the online systems. Calibration processes run on the online systems concurrently with the acquisition and sample events from DAQ memory buffers. These processes perform non-CPU-intensive tasks such as adjustment of the global time and energy scales for the EmC and monitoring of the time-to-distance relations for the DC. A complete and time consuming calibration is started from closed files only if the calibrations have changed significantly. Once the calibrations have been validated (typically within an hour of run closure), the reconstruction program processes the raw files. As output, the reconstruction program writes reconstructed-data files known as *datarec* files. Reconstructed events are significantly larger (12–15 KB) than raw events (∼2.5 KB). The reconstructed files are therefore used to produce DST files that contain an essential summary of physics-related quantities for each event, and in which the event size is much smaller (∼3 KB). The DST's are the starting point for most user physics analysis.

Monte Carlo (MC) production follows a similar scheme. The simulation executable generates events and writes them to Monte Carlo output (*MCO*) files, which are then reconstructed in a separate process. During the reconstruction, background extracted from reconstructed events in the data set is overlaid with the events as generated. The information in the MCO files is completely subsumed by that in the reconstructed Monte Carlo files (*MCR* files), so the MCO files are deleted as the MCR files become available. Due to the need to retain information describing the events as generated, events in MCO and MCR files occupy about 20 and 30 KB, respectively, *i.e.*, they are significantly larger than their counterparts in the data set. MCR files are also subject to data reduction; MC DST's are produced in a manner identical to that for datarec files (see Section V-B).

KLOE data are written in YBOS format [4]. In datarec, MCR, and DST files, YBOS-formatted events are compressed with ZLIB routines [5], which reduces the data volume by 40%.

III. Data Handling

A diagram of the data-handling scheme is presented in Fig. 2. Raw files are written to 1.4 TB of disk locally mounted on the online servers. These files are then asynchronously archived to the tape library over an NFS mount. The archiving processes are tailored to minimize the number of tape mounts while guaranteeing enough space on the disk pool. In most cases, reconstruction is performed while the raw files are still resident on disk. For input to the reconstruction processes from the online disk, events are either read across an NFS mount or served by the data-handling system using a custom TCP/IP protocol, which is provided by the *KLOE Integrated Dataflow* package (KID) [6]. Reconstruction output is written via NFS to an offline disk pool, from which it is asynchronously archived to tape. DST's for each run are produced from the corresponding datarec files, often immediately after the run has been completely reconstructed. In this case, the reconstructed

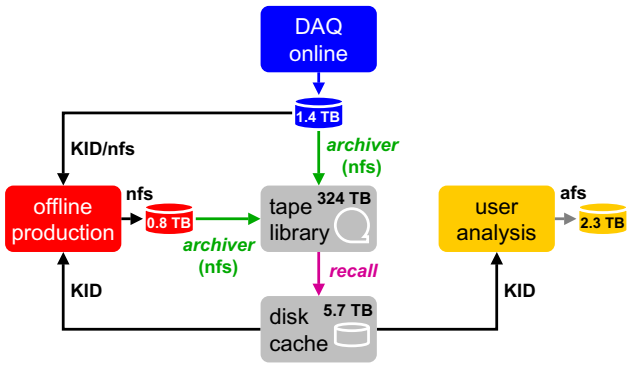

Fig. 2. Schematic view of KLOE data handling

events may be read back in across the NFS mount for the data reduction processes. When files already archived and deleted from the online or offline disk pools must be processed on the offline farm, the data-handling system restores the relevant input from tape to a 5.7 TB recall disk cache, from where they are served to the offline processes using the KID protocol. The same access model applies to user jobs running on the analysis farm. In principle, users may need to analyze raw, datarec, or DST files. If the files requested are resident on the online or offline disk pools, they are copied to the recall disk cache by the data-handling system to be served to the user processes; otherwise, they are restored to the recall disk cache from tape. Generally, however, only DST files are of interest to the users. A large fraction of the recall disk cache is therefore allocated to ensure high disk latency for DST's.

A central database based on IBM's DB2 [7] is used to keep track of the locations of the several million files comprising the data set. Each file is logged in the database when it is created. The database entry also contains the reconstruction status of the file, allowing files that require processing to be easily identified.

The backbone of the data-handling system is the KID package, which consists of two pieces: a centralized data-handling daemon, which coordinates the distributed file moving services; and a client library, with an easy-to-use URL-based interface that allows access to files independent of their locations. KID URL's may incorporate SQL queries used to interrogate the bookkeeping database. Examples include:

- All raw files in the stated run range that have not yet been reconstructed:
  dbraw:run_nr between 23000 and 24000 and analyzed is not null
- All reconstructed files in the $K_S K_L$ stream for a given run:
  dbdatarec:run_nr = 23015 and stream_code = 'ksl'

The database and data-handling server is an IBM F50 running AIX with four 166-MHz PowerPC CPU's and 2 GB of RAM. Two IBM H80's running AIX, each with six 500-MHz RS64-III CPU's and 2 GB of RAM are used as file servers for the offline disk pool, recall cache, and tape library. With the two file servers working in concert, aggregate I/O rates of over 100 MB/s have been obtained. Each file server is connected to 1.8 TB of Fibre Channel (FC) and 1.4 TB of

SSA disks (configured in striping mode), as well as to the experiment's IBM 3494 tape library, which has 12 Magstar 3590 tape drives, dual active accessors, and space for about 5400 60 GB cartridges. The tape library is maintained using IBM's Tivoli Storage Manager [8].

Network connections are routed through a Cisco Catalyst 6000 switch. The file and AFS servers are connected to the switch via Gigabit Ethernet. Connections to all other nodes are via Fast Ethernet.

IV. Online Computing

The DAQ and online systems were designed to sustain a bandwidth of 50 MB/s from detector to tape. The online farm consists of seven IBM H50 servers running AIX, each with four 332-MHz PowerPC 604e CPU's and 270 GB of local disk. In 2002, three of these servers were used for tasks strictly related to the acquisition of data, while the others were used for calibration and monitoring. If needed, all seven servers can be used for DAQ-related tasks.

The processes running on each of the three servers dedicated to online tasks are illustrated in Fig. 3. Sub-events from the acquisition chains are routed through a Digital FDDI Gigaswitch to the online servers in such a way as to distribute the load evenly among the nodes. On the servers, the sub-events are assembled into complete events and formatted by an event-builder process. Events flagged as cosmic rays (CR's) by the hardware level-2 trigger are then subject to review by the level-3 trigger implemented in software. For some types of events (*e.g.*, $e^+e^- \to \mu^+\mu^-(\gamma)$ and $e^+e^- \to \pi^+\pi^-(\gamma)$), enforcing the CR veto at level 2 incurs notable inefficiencies. At level 3, a fast reconstruction is performed, which allows for better discrimination of CR events. Events passing the level-3 trigger are recorded and asynchronously archived to tape. A number of spy daemons review buffered events before and after the level-3 trigger and select certain event types (Bhabha, CR, etc.) for calibration and monitoring purposes. These events are then written to a circular buffer, from which they are served by KID to the appropriate processes.

Each online server can handle a maximum rate of at least 2.4 kHz. For comparison, in 2002, with an average luminosity of 4×10^{31} cm^{-2} s^{-1}, the level-2 rate (without enforcement of the CR veto) was about 3.5 kHz. This rate was divided among three servers, with up to seven available. The installed online CPU power is more than adequate to meet the needs of the experiment for the foreseeable future.

V. Offline Computing

The machines for the offline and analysis farms are a mix of IBM B80 servers running AIX, each with four 375-MHz Power3 CPU's; and Sun E450 servers running Solaris, each with four 400-MHz UltraSPARC II CPU's. In all, 23 B80's and 10 E450's are available. Currently, 16 to 19 B80's and 8 E450's are used for the offline farm. The partitioning is flexible enough to allow machines to be transferred between the offline and analysis farms as the need arises. The offline and analysis

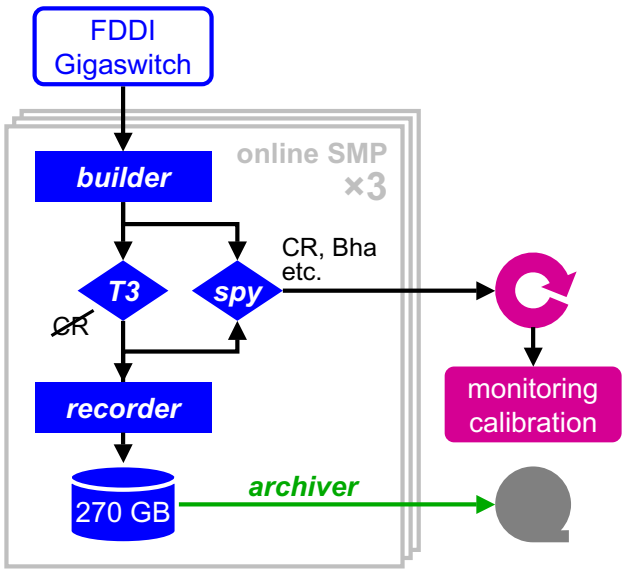

Fig. 3. Processes running on a single online server.

software framework is provided by ANALYSIS_CONTROL [9], with various customizations for KLOE, such as the introduction of the KID interface.

A. Reconstruction and DST Production

The tasks performed during event reconstruction are summarized in the upper part of Fig. 4. Raw events are first reconstructed in the EmC. The EmC reconstruction is fast (4 ms per event[1]), and yields cluster coordinates, energies, and times. This information is sufficient to allow rejection of a significant portion of the machine background, as well as of essentially all cosmic-ray events residually present. Only about 40% of the input rate passes the filter. Reconstruction in the DC includes pattern recognition, track fitting, and vertex finding, and is the most CPU-intensive reconstruction task. On average, DC reconstruction takes about 40 ms per event for events passing the filter, where this number is a sample-weighted average of the reconstruction times for Bhabha events (∼30 ms), ϕ-decay events (∼120 ms), and a small fraction of unrejected background events (15–40 ms). After reconstruction in the DC, events are classified into streams on the basis of topological information and written to separate datarec files. At present, five streams are defined for K^+K^-, K_SK_L, $\rho\pi$, radiative ϕ, and Bhabha events. Events may be written into more than one stream in principle; in practice, the overlap between streams is minimal. The files for each stream (with the exception of that for Bhabha events) are then used to make DST's.

DST production proceeds in three stages as illustrated in the lower diagram of Fig. 4. First, a more refined event selection may be applied, in order to reduce the stream volume. Second, any topology-specific algorithms necessary to complete

[1]Throughout this paper, all CPU times are referred to a single 375-MHz Power3 processor installed in an IBM B80 server

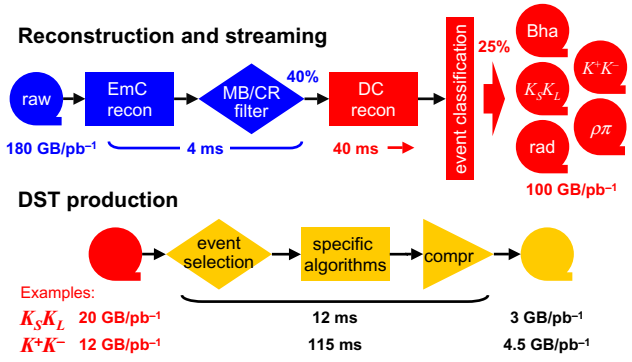

Fig. 4. Flow charts for offline production. Top: Reconstruction and streaming. Bottom: DST production. All numbers are indicative and refer to 2001–2002 averages.

reconstruction of the stream are run. Finally, a set of bank-selection and compression routines are applied. In the DST production for any given stream, the first two stages may or may not run; the last stage runs always. As a performance example, consider the K_SK_L stream. The completion of all three stages takes about 12 ms per event and results in a reduction of the data volume by a factor of more than six. Because of the low velocities of charged kaons at KLOE ($\beta \approx 0.2$), K^+K^- events must be completely retracked once identified. As a result, DST production for the corresponding stream takes 115 ms per event, and the data volume is slightly larger than it is for the other streams because of the additional information retained.

B. Monte Carlo Production

The other significant task that runs on the offline farm is MC production. In particular for the study of physics backgrounds to some of the rarer decay channels, we require MC event samples that are of statistical significance comparable to the data set itself. MC production campaigns currently running include $\phi \rightarrow$ all final states at a luminosity scale of 1:5 (2.6×10^8 events) and $\phi \rightarrow K_SK_L \rightarrow$ all final states at a scale of 1:1 (4.3×10^8 events). An interesting aspect of KLOE MC production is that runs in the data set are individually simulated. Specifically, an MC sample is generated for each run in the data set, with the number of events proportional to the integrated luminosity of the run under simulation, and such parameters as machine energy, momentum of the collision center-of-mass, beam-spot position, map of dead detector elements, and trigger thresholds set to correspond to the run conditions. The set of MC events for any group of runs thus automatically reflects the correct average over these time-variable conditions. The simulation itself is based on GEANT 3.21 [10], with a full suite of dedicated ϕ and secondary decay generators and full digitization of the detector response. Accidental activity in the EmC and DC is sampled from $e^+e^- \rightarrow \gamma\gamma$ events in the data set and inserted into the MC events run-by-run, with care taken to preserve the temporal profile of the background levels within each run. During reconstruction of MC events, the filtering and event-classification algorithms register their decisions in the data stream. The filters are not enforced, however, and the reconstructed events are not streamed into separate files. Instead, streaming is performed at the DST-production stage. In addition to the events classified on the basis of reconstructed quantities, each MC DST stream contains all events with topologies as-generated relevant to the physics of the stream.

VI. Analysis Environment

Users produce histograms and Ntuples for their analyses on the analysis farm, which consists of four to seven IBM B80 and two Sun E450 servers. Three of the B80's are typically reserved for batch jobs, with queues managed by IBM's LoadLeveler [11].

Analysis jobs usually use DST's as input. For the 2001–2002 data, the set of DST's occupies 4.1 TB; MC DST's occupy an additional 3.1 TB. Copies of the bulk of the DST's reside on the 5.7 TB recall disk cache (Section III) with high latency. Output is written to user and working group areas on the KLOE AFS cell. The AFS cell is served by two IBM H70 servers, each with four 340-MHz RS64-III CPU's, 850 GB of SSA disks, and 250 GB of FC disks (2.3 TB total). Users can access the AFS cell from PC's running Linux on their desktops to perform the final stages of their analyses.

As an example, consider the analysis of the 2001–2002 K_SK_L data set, which consists of 7×10^8 events, or 1.4 TB of DST's. The typical time needed for a user to analyze the entire data set on the farm is six days elapsed with six jobs running in parallel (the default maximum). The typical output size ranges from 10 to 100 GB, which can be accessed *in situ* on the AFS cell or copied off to a user's desktop PC.

VII. CPU Power and Mass Storage Requirements

During the years 2001 and 2002, the average DAΦNE luminosities were about 2×10^{31} and 4×10^{31} cm^{-2} s^{-1}, respectively. In 2001, the input rate to the offline system was determined by the level-2 trigger rate, and was 2.0 kHz on average. In 2002, the implementation of the level-3 trigger (which obviated the need for collection of a sample of prescaled CR veto events), together with decreased machine background levels, reduced the offline rate to 1.6 kHz. The DAΦNE upgrade carried out in the first half of 2003 is predicted to further increase the peak luminosity, to 2×10^{32} cm^{-2} s^{-1}, with favorable background conditions. In the following, our predictions for the 2004 run assume an average luminosity of 1×10^{32} cm^{-2} s^{-1} and background levels identical to those of 2002. The predicted level-3 rate is then 2.1 kHz. Current plans call for approximately a year of running, which would allow for the collection of 2 fb^{-1} in 2004.

A. Processing Requirements

For the 2001 and 2002 data, about 40% of the input rate required reconstruction in the DC, and about 20 ms were needed to reconstruct an event on average. For 2004, the

TABLE I
CPU'S REQUIRED FOR OFFLINE TASKS

	2001	2002	2004 (est.)
Reconstruction	42	30	71
DST production	2	5	13
Monte Carlo	11	23	63
TOTAL	55	58	147

TABLE II
SIZE OF KLOE DATA SETS, IN TB

	2001–2002	2004 (est.)
Raw files	102	100
Datarec files	51	192
MCR files	25	86
DST files	7	32
TOTAL	185	410

fraction of events reconstructed in the DC is expected to rise to 60%, which leads to an event reconstruction time of 33 ms. We will also have to produce DST's for a fraction of the input rate corresponding to $\sim$330 Hz, at 38 ms per event summed over all streams. Finally, assuming that MC production plans remain the same, we will need to generate, reconstruct, and produce DST's for MC events at an equivalent rate of $\sim$170 Hz, with $\sim$200 ms per event required for generation, and $\sim$375 ms per event required in total. These considerations lead to Table I, in which we list the number of CPU's needed for the various offline tasks to keep up with the data acquisition. We can usually allocate at most 76 CPU's to offline production. While this has been more than sufficient to handle the load so far, for 2004, we will have to roughly double the amount of offline CPU power available.

B. Mass Storage Requirements

In Table II, we list the total volume of KLOE data by file type (DST volumes for data and MC are summed in the table). For the 2001–2002 data, background events contribute significantly to the raw data volume, and raw files occupy the most space. Because of the increased luminosity and favorable background levels predicted for 2004, the volume of the reconstructed data is expected to surpass that of the raw data, and MC events are expected to occupy a considerable volume. The maximum capacity of the current tape library is 324 TB. For 2004, we will need at least an additional 300 TB of tape storage capacity. In addition, the need to maintain a significant fraction of 32 TB of DST's on disk calls for the recall disk cache to be significantly enlarged.

VIII. PLANNED UPGRADES

Current plans call for the addition of ten new IBM p630 servers to the offline farm, each with four 1.45-GHz Power4+ processors. This solution would supply the increase in processing power needed to handle the 2004 data. We note that the KLOE offline software is portable, and that we were not bound to IBM platforms when planning for the upgrade. After bids were solicited from various suppliers, however, this solution proved to be cost-competitive with alternate solutions based on Linux systems with x86-compatible CPU's, and offered additional convenience in terms of ease of integration with our current offline system. Together with the CPU upgrade, we plan to add about 20 TB of FC disks to the recall cache and AFS cell.

Finally, we will extend our long-term storage capacity. The solution under consideration is the installation of a second IBM 3494 tape library. The new library would use six Magstar 3592 drives, which can write 300 GB to a cartridge in native format, and which can read and write at 40 MB/s [12]. The initial installation would include 1000 cartridges with space for 3600, which would allow the total capacity of the new library to be expanded from 300 TB to 1.08 PB as needed. The new library will have an FC interface. Since the library must be installed in a separate building 200 m from the KLOE computer center, a storage area network will be deployed to connect the library to the file servers.

IX. CONCLUSIONS

The KLOE computing environment is flexible and scalable. In normal running, the system smoothly serves data to hundreds of contemporary processes related to the storage, reconstruction, and analysis of a data set consisting of nearly 200 TB. Our experience concerning the scalability of the environment leads us to believe that with the extensions described here, the system should easily be able to handle data collection rates of greater than 10 pb^{-1}/day when data taking restarts after the DAΦNE luminosity upgrade.

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