NA62

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1 The NA62 Experiment

The branching ratio (BR) for the decay $K^+ \to \pi^+ \nu \bar{\nu}$ can be related to the value of the CKM matrix element V_{td} with minimal theoretical uncertainty, providing a sensitive probe of the flavor sector of the Standard Model. The measured value of the BR is $1.73^{+1.15}_{-1.05} \times 10^{-10}$ on the basis of seven detected events [1]. The goal of the NA62 experiment at the CERN SPS is to detect ∼100 $K^+ \to \pi^+ \nu \bar{\nu}$ decays with a S/B ratio of 10:1 [2]. The experimental layout is illustrated in Fig. 1.

The experiment will make use of a 75 GeV unseparated positive secondary beam. The total beam rate is 800 MHz, providing ∼50 MHz of K^+'s. The decay volume begins 102 m downstream of the production target. 5 MHz of kaon decays are observed in the 65-m long fiducial vacuum decay region. Ring-shaped large-angle photon vetoes are placed at 12 stations along the decay region and provide full coverage for decay photons with 8.5 mrad $< \theta <$ 50 mrad. The last 35 m of the decay region hosts a dipole spectrometer with four straw-tracker stations operated in vacuum. The NA48 liquid krypton calorimeter [3] is used to veto high-energy photons at small angle. Additional detectors further downstream extend the coverage of the photon veto system (e.g. for particles traveling in the beam pipe).

The experiment must be able to reject background from, e.g., $K^+ \to \pi^+ \pi^0$ decays at the level of 10^{12}. Kinematic cuts on the K^+ and π^+ tracks provide a factor of 10^4 and ensure 40 GeV of electromagnetic energy in the photon vetoes; this energy must then be detected with an inefficiency of $\leq 10^{-8}$. For the large-angle photon vetoes, the maximum tolerable detection inefficiency for

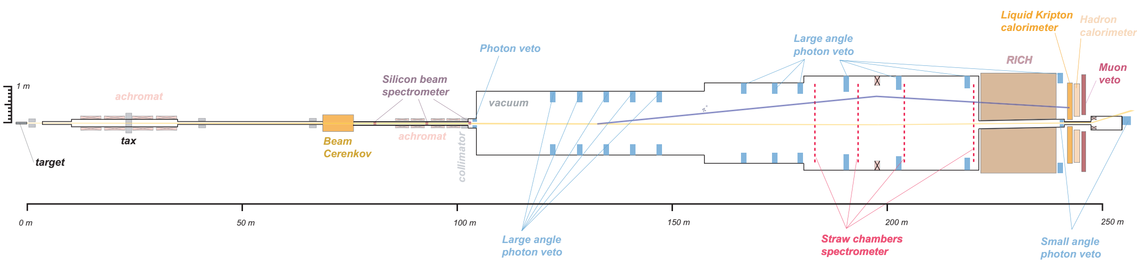

Figure 1: *The NA62 experimental layout.*

photons with energies as low as 200 MeV is 10^{-4}. In addition, the large-angle vetoes (LAVs) must have good energy and time resolution and must be compatible with operation in vacuum.

The principal involvement of the LNF NA62 group is in the design and construction of the LAV system.

In 2012, the main responsibilities of the LNF NA62 group were the following:

- Continued processing of lead-glass blocks for use in LAV stations A9, A10, and A11 (structural reinforcement, cleaning, characterization, and testing).
- Assembly and transport to CERN of A8 and A11.
- Production of final drawings for station A12, which is operated in air and thus of a different design from the other stations.
- Installation of the first 8 stations into the NA62 beamline.
- Vacuum-testing and measurement of outgassing for the stations installed.
- Mass production and testing of the LAV front-end electronics boards.
- Commissioning of the electronics for the first 3 stations.
- Development of level-zero trigger firmware for the LAV system.
- Coordination of the NA62 Photon Veto working group.

2 Large-Angle Photon Vetoes

The LAV design is based on the reuse of the lead-glass blocks from the central part of the OPAL electromagnetic calorimeter barrel [4]. The blocks are made of SF57 lead glass and have an asymmetric, truncated square-pyramid shape. The front and rear faces of the blocks measure about 10×10 cm^2 and 11×11 cm^2, respectively; the blocks are 37 cm long. The modules are read out at the back side by Hamamatsu R2238 76-mm PMTs, coupled via 4-cm cylindrical light guides of SF57. The LAV system consists of 12 stations. The diameter of the stations increases with distance from the target, as does the number of blocks in each, from 160 to 256, for a total of about 2500 blocks. Each station consists of four or five rings of blocks, with the blocks staggered in azimuth in successive rings. The total depth of a five-layer station is 27 radiation lengths. This structure guarantees high efficiency, hermeticity, and uniformity of response. The final design for the first five stations is illustrated in Fig. 2, left.

2.1 LAV construction and installation at CERN

The first LAV station, ANTI-A1, was constructed in 2009 and served as a prototype; three more of the upstream LAV stations, ANTI-A2, A3, and A4, were built at LNF during 2010. In 2011, with the construction of A5, the series of stations of small diameter was completed. Stations A6 and A7, of intermediate diameter, were also constructed in 2011 [5]. Following the delivery of A7 to CERN in early 2012, stations A8 and A11 were constructed and delivered. A11 was the first station of large diameter to be completed and required the development of new technical solutions for aspects of the cabling and assembly. As of the end of 2012, 9 of the 12 stations have been completed and delivered to CERN. So far during the construction of the LAV detectors, more than 1760 lead-glass blocks from the OPAL electromagnetic calorimeter have been processed (structural reinforced, cleaned, characterized, and tested), corresponding to $\sim 70\%$ of the total to be used in NA62.

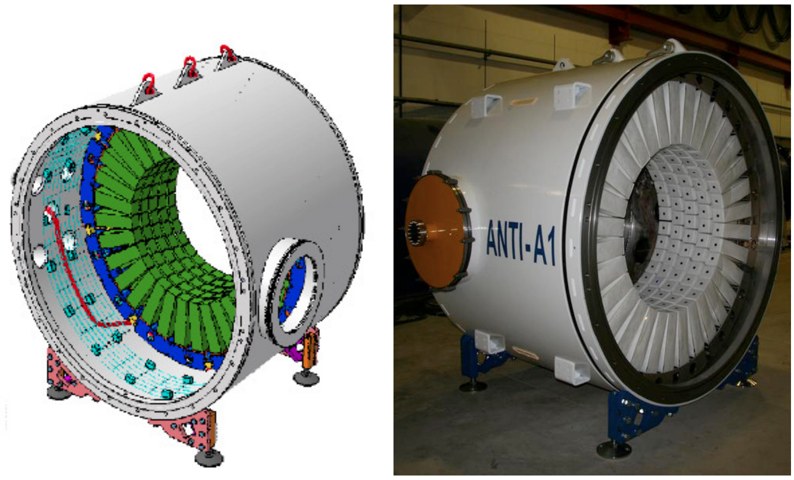

Figure 2: *Left: Design study for the upstream LAV stations. Right: Photograph of the prototype ANTI-A1.*

Much progress has also been made on the mechanical design for stations A9 and A10. Since these two stations will be operated in the vicinity of the NA62 spectrometer magnet, the vacuum vessels in which they are housed must be constructed from high-quality, non-magnetic stainless steel. In 2012, significant effort was dedicated to identifying and procuring an appropriate grade of non-magnetic stainless steel, and to developing techniques for its machining and welding. The contract for the fabrication of the vessels for A9 and A10 was awarded to Fantini SpA in mid-2012, with whom this work was carried out in collaboration. Construction of the A9 vessel was begun in September and for the A10 vessel shortly thereafter. These vessels are expected to be delivered to Frascati during the first half of 2013.

By the end of 2012, the basic design of the A12 station was completed. In particular, the arrangement of the blocks, the mechanical structure, and the basic cabling scheme were all finalized. The design of the A12 station, illustrated in Fig.3, is different from that of the other 11 stations in many important aspects: it is operated in air rather than in vacuum, it is modular rather than monolithic because of its large size, and its installation into the closed space at the downstream end of the beamline will require a delicate insertion procedure.

Also in 2012, stations A1 to A8 were installed in the beamline and vacuum tested. A11 was not installed only because the beam line is not yet ready at the installation point. The installation required a total of 26 person-weeks of continuous presence at CERN. In August, stations A1 to A3 were cabled, equipped with front-end electronics and digital readout cards, and read out with the NA62 data acquisition system in preparation for the first NA62 technical run, which took place in November 2012 (see Fig. 6).

3 LAV readout

The LAV system will mainly detect photons from kaon decays, as well as muons and pions in the beam halo. For each incoming particle, the veto detectors are expected to provide a time measurement with $\sim$1 ns resolution and an energy measurement of moderate precision (of order 10%). The system must be able to operate with thresholds of a few millivolts, well below the signal amplitude for minimum-ionizing particles (MIP) traversing the blocks, in maintain the detection efficiency as high as possible for muons and low energy photons.

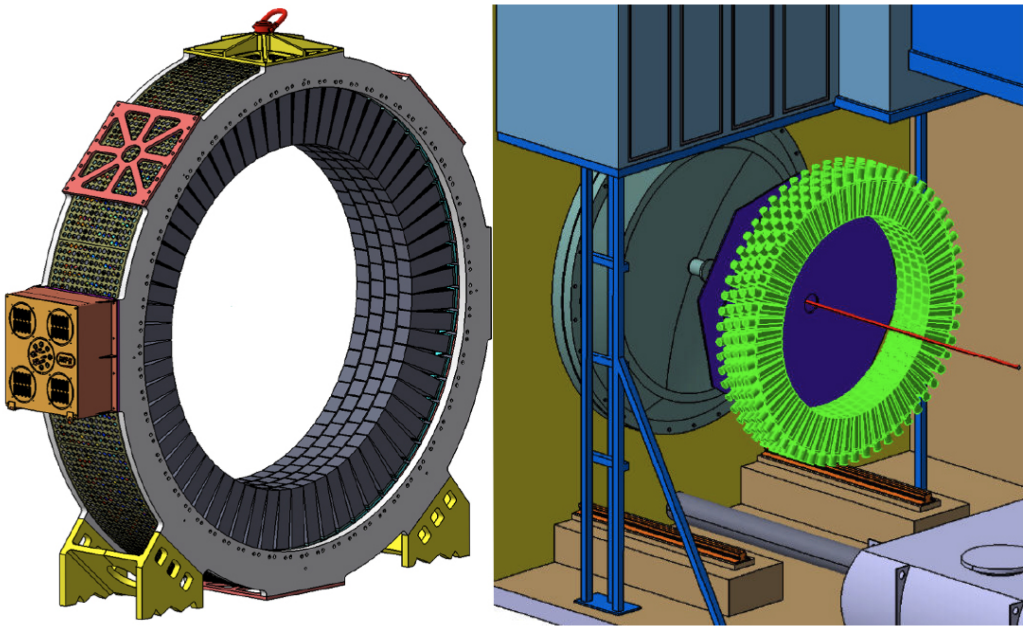

Figure 3: *The LAV ANTI-A12 station (left) and its insertion point in the NA62 experimental hall (right).*

Because of the intrinsic time resolution of the lead-glass blocks (<1ns) and the rise time of the Hamamatsu R2238 PMTs (∼5 ns), the requirements on the precision of the time measurement are not stringent. On the other hand, the amount of energy deposited in the LAV stations from photons from π^0 decays spans a very wide range, from 10 MeV up to 30 GeV. Using the measured average photoelectron yield of 0.3 p.e./MeV and a nominal gain of $1 \cdot 10^6$ for the R2238 PMT, one expects a signal charge of ∼4.5 pC for a MIP, corresponding to a signal amplitude of ∼20 mV on a 50Ω load. At the upper end of the photon energy range, signals from 20 GeV showers can reach an amplitude of 10V. The readout chain for the LAV stations consists of two different types of boards

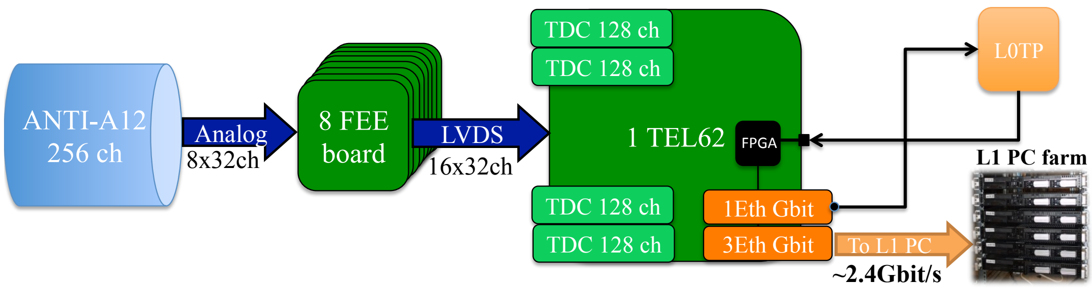

Figure 4: *The LAV readout scheme. The ANTI-A12 station has been used as example.*

(see Fig. 4): a dedicated front-end board developed for the LAV detector, and a common digital readout board called TEL62, used by most of the NA62 detectors. The LAV front-end board splits the analog signal from the PMT into two copies and converts each into a logical LVDS signal, using two comparators with independently adjustable thresholds. The duration of the LVDS pulses is

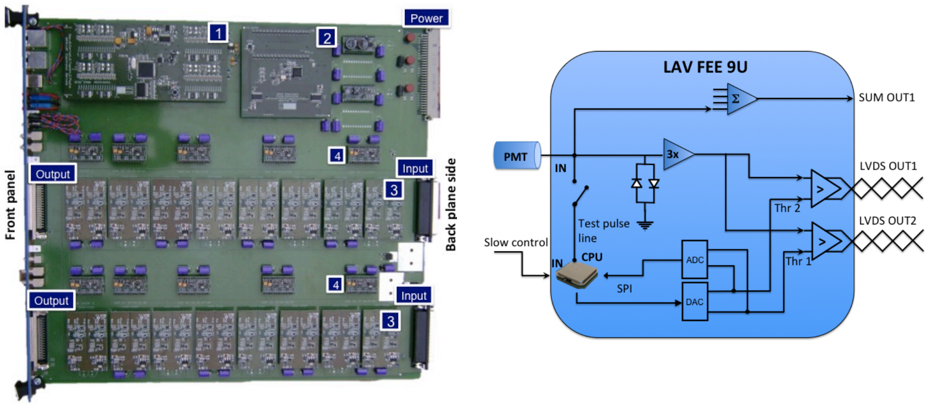

Figure 5: *The LAV front end board (left) and its block diagram (right).*

equal to the time during which the analog signal is above the programmed threshold. The LVDS logic signals are sent to the TEL62 readout board, in which a custom-designed TDC mezzanine converts each signal into digital leading and trailing times. The FPGAs on board the TEL62 are used to correct raw hit times for slewing and to produce a level-zero (L0) trigger primitive (see Fig. 5), which is sent to the L0 trigger processor using a dedicated gigabit Ethernet interface. Upon receiving a L0 trigger request, the TEL62 sends its buffered data to the level-one (L1) PCs over three additional gigabit Ethernet interfaces. The whole LAV system has ~ 2500 analog input channels and ~ 5000 digital output channels in total. The system is designed to sustain hit rates of up to 100KHz per channel and to be able to transmit a data volume to the L1 PC farm of up to 2.4 Gbit/s for each station.

3.1 LAV front-end electronic board

Since 2010, the LNF group has been responsible for the design and construction of the front-end electronics for the large-angle veto system. The basic idea is to exploit the time-over-threshold technique to measure the signal charge over a broad interval. A custom 9U board designed by the LNF Servizio di Elettronica converts the analog signals from the PMTs into logical LVDS signals of equivalent width, as described above. The LAV front end board is implemented on a 9U VME standard layout with the J1 power connector only at the top of the backplane side. No VME bus line is connected to the board; only custom ± 7.5 V power lines are used. At the bottom, the 32 analogue inputs are connected to the board using two DB37 connectors (see fig 5). The signal from each analog input channel is discriminated at two different, programmable levels to produce two logical outputs. The resulting 64 LVDS outputs are available on two SCSI2 connectors placed on the front panel of the board for connection to the TDCs. Analog sums of groups of 4 and 16 channels are provided on 8 + 2 LEMO00 connectors for monitoring of the analog signals. Communications with the board (e.g., for threshold programming) are managed by the CAN-Open protocol via two RJ-45 connectors. To simplify maintenance and reduce costs, the board has a modular structure. The 9U motherboard manages input, output, and power distribution while all other functions are implemented on mezzanines of four different types. A detailed description of each mezzanine can be found in [6]. Five prototype 9U boards complete with their mezzanines were assembled and tested in 2011.

The year 2012 was dedicated to the mass production and testing of LAV front-end boards. One-hundred fully equipped boards have been produced, for a total of 1600 time-over-threshold mezzanines. Thirty boards were tested and characterized in advance of the NA62 technical run in November 2012 (see Fig. 6). The characterization and testing was performed at LNF using the automatic system described below. Twenty-six of these were delivered to CERN and installed for the technical run.

4 Testing LAV front-end boards

In order to test and characterize the 100 LAV front-end boards, an automated test stand was set up at LNF at the beginning of 2012.

4.1 Test setup

A pulse generator (Agilent 81110A) is used to generate test signals with a fixed rise time of 5 ns, a fall time of 16 ns, and variable amplitude. The signal is passively split into 32 copies and fed into the input DB37 connectors of a front-end board. The 64 LVDS outputs are connected to a VME commercial board (CAEN V1190B), which makes use of the same TDC ASIC as the actual TEL62 readout (HPTDC). The digital data from the TDCs are collected through a VME controller (CAEN V1718) and stored on a PC. The PC additionally sets the threshold values on the front-end boards via USB, and varies the amplitude of the signals from the pulse generator via GPIB. The procedure is fully automated; a complete test of a front-end board takes about 15 minutes.

4.2 Test results

Minimum threshold and time resolution measurements are performed for each board.To determine the minimum threshold, the amplitude of the input signal is varied over the range from 5 mV up to 20 mV. The threshold is set to the nominal value of 2 mV. This is the lowest value at which the noise rate is less than 100 Hz on each channel. The efficiency for each channel is measured as the number of pulses detected divided by the number delivered. An example of the result of this measurement is shown in Fig. 6, left. The minimum threshold is defined as the smallest value of the signal amplitude for which the efficiency is greater than 95%, as illustrated in the figure by the dashed red lines.

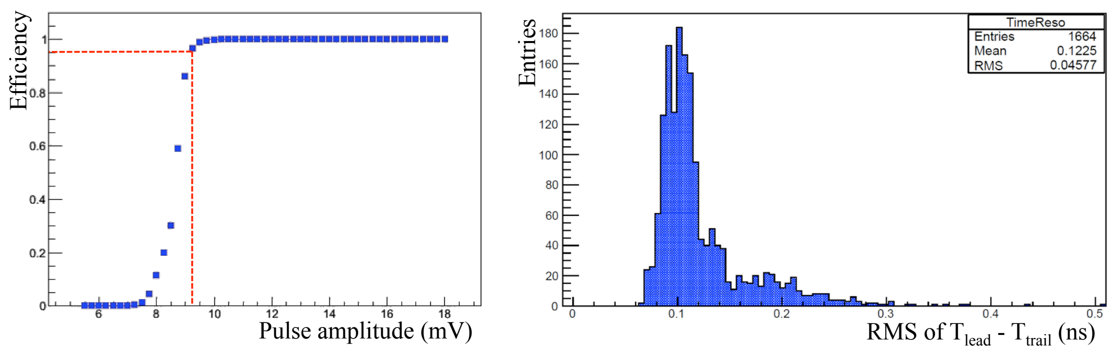

Figure 6: *Left: threshold profile. Right: distribution of the RMS of repeated time measurements of a probe signal, performed with every channel. The probe signal has an amplitude of 100 mV and a fixed width of 30 ns to within 40 ps RMS.*

The time resolution is obtained by performing repeated measurements of the time difference between the leading and the trailing edges of a test input signal. The test signal is supplied by a pulse generator with a width of 30 ns and an RMS variation of less than 40 ps. The time resolution is then evaluated as the RMS of the distribution of the leading-trailing time difference. The distribution of the resulting values of the time resolution, for all channels on 26 boards, is shown in Fig. 6, right. Most channels have a time resolution on the order of 100 ps. The tail towards higher values is due to noisy channels that are still under study. If needed, the performance of these channels can be improved by replacing the noisy ToT mezzanines, thanks to the modular design of the front-end board.

5 LAV trigger-generating firmware

For all of the NA62 detectors, the digital readout is based in the TEL62 board [7], which collects the data from TDC mezzanines and transfers them to the L1 PC farm via a gigabit Ethernet link upon receipt of a L0 trigger. Some of the detector subsystems, including the LAVs, must also generate the L0 trigger primitives. An L0 primitive is the value of the time at which some specific physics event occurred. To recognize this event and generate the primitive requires the development of detector-specific firmware for the FPGAs on board the TEL62s. In the case of the LAVs, the event which causes an L0 primitive to be generated is simply the receipt of a signal crossing both the low and high thresholds on the same block.

In 2012, the firmware to generate the L0 primitive for the LAVs was developed at LNF. The data stream for L0 primitive generation is independent of and parallel to that for the acquisition of LAV data. As a first step, events are distributed among different FIFOs, one for each low and high threshold channel. While the FIFOs are filled, a finite state machine searches for an event, i.e., a block with both thresholds crossed. Once the two hits are associated, the event time is determined, with slewing (time-walk) corrected according to the following formula:

$$t = t_{low} - \frac{(t_{high} - t_{low}) \cdot t_{low}}{V_{high} - V_{low}}$$

where V_{high} and V_{low} are the high and low threshold voltages and t_{high} and t_{low} are the respective crossing times. Events occurring within a specific time window (programmable up to $\sim$ 25 ns) are then grouped together to form a cluster whose time is calculated as the average of single times. Finally, the time values of the clusters are sorted and delivered to the last firmware block to build the trigger primitives and send them to the experiment's L0 trigger processor.

6 NA62 Technical Run

The first NA62 technical run was carried out in November 2012. The goal of this run was to test the full readout chain and data acquisition system. The detectors involved in the test were the charged and neutral hodoscopes from NA48 (CHOD and NHOD), the charged-particle veto (CHANTI), LAV stations A1 to A3, muon vetoes (MUV) 1 to 3, the small-angle photon veto (SAC), and the beam Cerenkov counter (CEDAR). The LAV front-end boards were used to read out most of the detectors involved in the test. The 26 LAV front-end boards available were installed in the readout chains of the CHOD (4 boards), NHOD (1), LAV (15), MUV (4), SAC (1), and CHANTI (1). The summed analog outputs from the front-end boards used to read out the CHOD and NHOD were used to produced a one-track L0 trigger signal for all detectors for the entire run.

During the technical run, three complete LAV stations were powered up with the definitive HV systems and data were acquired with the final acquisition chain with muon and kaon beams. The entire readout chain was tested, with data recorded in the L1 PC farm. The data taken during the technical run were used to verify that all channels and the associated electronics for LAV stations 1 to 3 were fully operational.

7 Conference talks by NA62 LNF members

- A. Antonelli: Vulcano Workshop 2012 - Frontier Objects in Astrophysics and Particle Physics. Vulcano (ME), Italy, 28 May - 2 June 2012.
  Talk: "NA62 Experiment".
- M. Moulson: XVth International Conference on Calorimetry in High Energy Physics. Santa Fe NM, USA, 4 - 8 June 2012.
  Talk: "The NA62 large-angle photon veto system".
- T. Spadaro: VII International Workshop on Chiral Dynamics (CHIRAL2012). JLAB, Newport News, VA, USA, August 6 - 10, 2012.
  Talk: "ChPT studies at NA62".
- A. Antonelli: 20th Int. Conf. on SUSY and Unification of Fundamental Interactions. Peking University, Beijing, China, 13 - 18 August 13 2012.
  Talk: "Search for New Physics at NA62".
- F. Gonnella: Topical Workshop on Electronics for Particle Physics. Oxford (Oxfordshire), United Kingdom, 17 - 21 September 2012.
  Poster: "Performance of the NA62 LAV front-end electronics".
- M. Moulson: Particle Physics Seminar, Columbia University. New York NY, USA, 3 October 2012.
  Talk: "The NA62 experiment: Rare kaon decays at the CERN SPS".
- M. Raggi: Quark Confinement and the Hadron Spectrum X. Munich, Germany, 8 - 12 October 2012.
  Talk: "ChiPT tests at NA62".

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