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Change Control

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Change History

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1. Objective

The scope of this document is to provide the functional specifications of the Tagged Neutron Inspection System of the EURITRACK project.

It will describe:

- the functional specifications of the entire system as a global block
- the preliminary structure of the inspection system
- the functional specifications of the individual system parts

It will not include detailed technical description of the individual system parts that are foreseen to be described in the “TNIS elements specification” document (Internal deliverable ID.3.1).

2. Global functional specifications

The Tagged Neutron Inspection System (TNIS) should provide the capabilities and functionalities necessary to a custom operator in order to perform an inspection of a given region inside the container verifying that the results from the neutron interrogation are in agreement with the official cargo documents. To this end the TNIS should be able positioned to inspect a given portion of the cargo container following operations of the entire EURITRACK System and should:

- execute the neutron interrogation
- collect the data and feed the results to the Information System

The functional specifications of the TNIS derive primarily from the elaboration of previous documents expressing the user needs and the EURITRACK system specifications:

- D.2: “EURITRACK functional and technical requirements”
- ID.1.1: “Expression of custom needs”

The main requirements that the TNIS should satisfy are:

- It must be able to acquire the spectra from a number (16 in the present version of the system) of large efficiency gamma-ray detectors and from one specialized neutron detector in coincidence with the alpha particles associated with the emission of 14 MeV neutrons in the D+T reaction.
- The associated alpha particle detector (the alpha tracker), embedded inside a neutron generator will be made of 64 independent pixel, so that the each pixel will defined an

independent beam of tagged neutron. The alpha tracker will make use of scintillation detectors using YAP:Ce crystals.

- The neutron generator will produce 14 MeV neutrons by using the D+T reaction. Standard use of the generator is foreseen at 1×10^8 neutron/s. The neutron generator should comply with standard rules for the handling of radioactive material (because of the Tritium isotope used as target to produce neutrons).
- All detector used in the TNIS (alpha tracker, NaI(Tl) and neutron detectors) make use of Photomultipliers (PMT) for the read-out of the scintillation light. Each PMT need to be powered through a voltage divider by an independent HV supply.
- Anodic signals from the detectors will be processed by front-end electronic system. The count rate capability of the front-end electronics should assure state-of-art performance of the system. Fast electronics should allow to select fast coincidences between any of the tracker pixel detectors and any of the NaI(Tl) detectors.
- The temperature dependence of the anodic signals and/or possible drifts of the front-end electronics should be monitored by suitable sensors. Software tools should be provided to compensate for such effects. A feedback to the operator is foreseen
- Software selection of sub-sets of the 64 YAP:Ce cells of the tracker would allow to define the neutron beam(s) that is (are) inspecting the selected voxel and/or volume slices inside the cargo container.
- For each coincidence event the following parameters have to be stored:
    - The pulse height amplitude and the time of arrival of the associated alpha particle in one of the pixels of the alpha tracker;
    - The pulse height amplitude and the delay time (with respect to the detection of the alpha particle) of neutron and gamma-rays detected in one of the 16 large volume NaI(Tl) scintillators placed in three detector arrays: the REFLECTION ARRAY; the TRANSMISSION ARRAY and the TOP ARRAY.
    - The pulse height amplitude, the Pulse-Shape information and the delay time (with respect to the detection of the alpha particle) of neutron and gamma-rays detected by the specialized neutron detector placed inside the TRANSMISSION array.
- The measured delay time of neutron and gamma-rays with respect to the arrival of the alpha particles will be used to electronically select (by software) slices of the cargo container volumes among its depth.
- The collected events would be sorted to construct the following spectra:
    - The time-of-flight spectrum of the neutrons transmitted through the cargo container.
    - Integral time-of-flight spectra for each gamma detector (total counting, no energy selection)
    - The gamma-ray spectra (pulse height spectra) for each single NaI(Tl) detector in coincidence with the alpha particle pixels and the proper gate selected on the delay time spectra that identify the "suspect" region inside the cargo container.

- The gamma-ray spectra for each single NaI(Tl) detector in coincidence with the alpha particle pixels and the proper gate on the delay time that identify the “background region” inside the cargo container.
- Special gates on the measured delay time spectra will allow constructing the spectra of the events associated to random coincidences between alpha and gamma or neutron detectors.

The TNIS should be able to perform two different types of measurements depending on the contrast between cargo filling and the searched hidden material:

1) Voxel inspection (i.e. Inspection of a well defined voxel inside the cargo).
2) Full Cargo sampling (i.e. Inspection of the material as a function of depth inside the cargo in case of homogenous filling) for a selected position.

- Depending on the selected inspection mode, a number of final photon and neutron pulse height spectra will be constructed by using the spectra of individual detector and/or selections. These spectra will be processed by the EURITRACK Information System to
  - Compare the spectral shapes from actual measurements with a data base including results from Monte Carlo simulations as well as experimental data acquired in previous inspections.
  - Calculate elemental ratios in selected voxels and associated errors, taking into account attenuation effects.
  - Compare the determined elemental ratios with those of the hazardous (and optionally benign) materials for possible identification
  - Provide the inspector a response that, within a predefined confidence interval, the material has/has not been identified

3. TNIS architecture

The EURITRACK TAGGED NEUTRON INSPECTION SYSTEM will be structured in a modular way, i.e. it will be constituted by a number of independent functional modules each one executing a specific task in the overall system operation.

The preliminary TNIS architecture is described in figure 1. The final architecture could slightly deviate from this initial proposal whether required by technical constraints during the phase of detailed TNIS design.

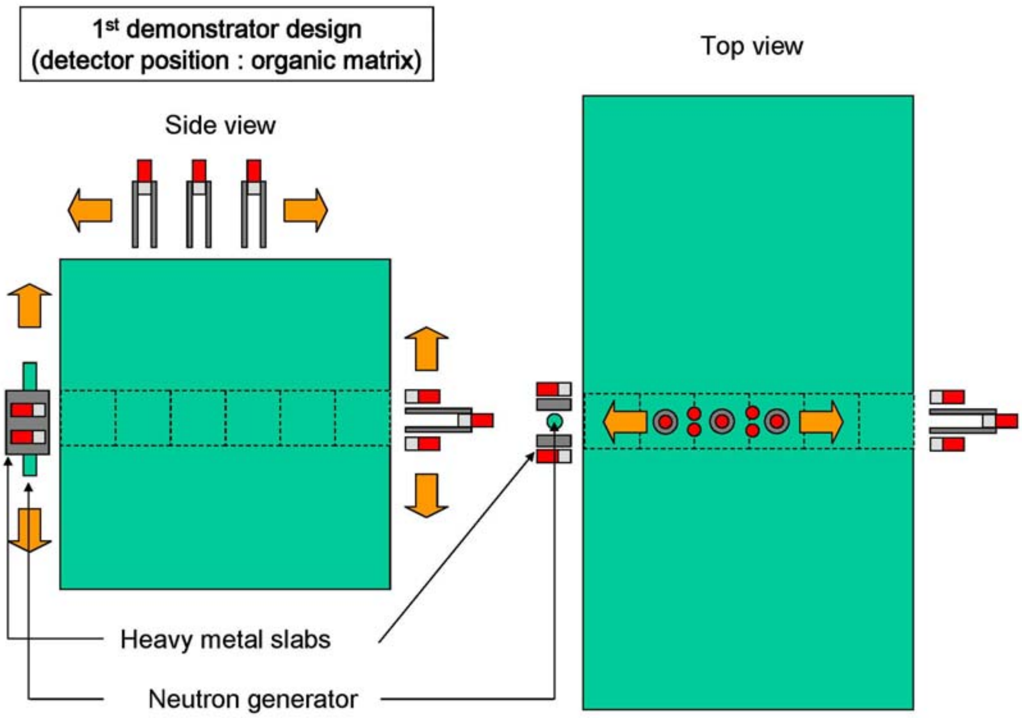
The main modules constituting the EURITRACK Tagged Neutron Inspection System are:

- The Neutron Generator
- The Alpha Particle tracker
- The detector arrays
- Front-end electronics

- Acquisition system

The functional specifications of the individual modules are described below.

Figure 1 – Preliminary view of the EURITRACK TNIS



4. Functional specifications of the individual modules

4.1 The Neutron Generator

4.1.1 General Presentation

Scope: to produce 14 MeV neutrons by using the D+T reaction.

The Neutron Generator is composed by two main hardware subsystems:

- The neutron emission module which contains the neutron tube with (indicated in the following as MEN TPA) and the isolating gas; the neutron emission module is embedded on the Reflexion Detectors Array and Neutron source module (RDAN)
- The electronic cabinet containing the gauge, the generator control unit and the Very High Voltage (VHV) power supply of the tube target;

The two subsystems are connected by VHV and Low voltage cables having 15m length. They are implemented in such a way the RDAN can move

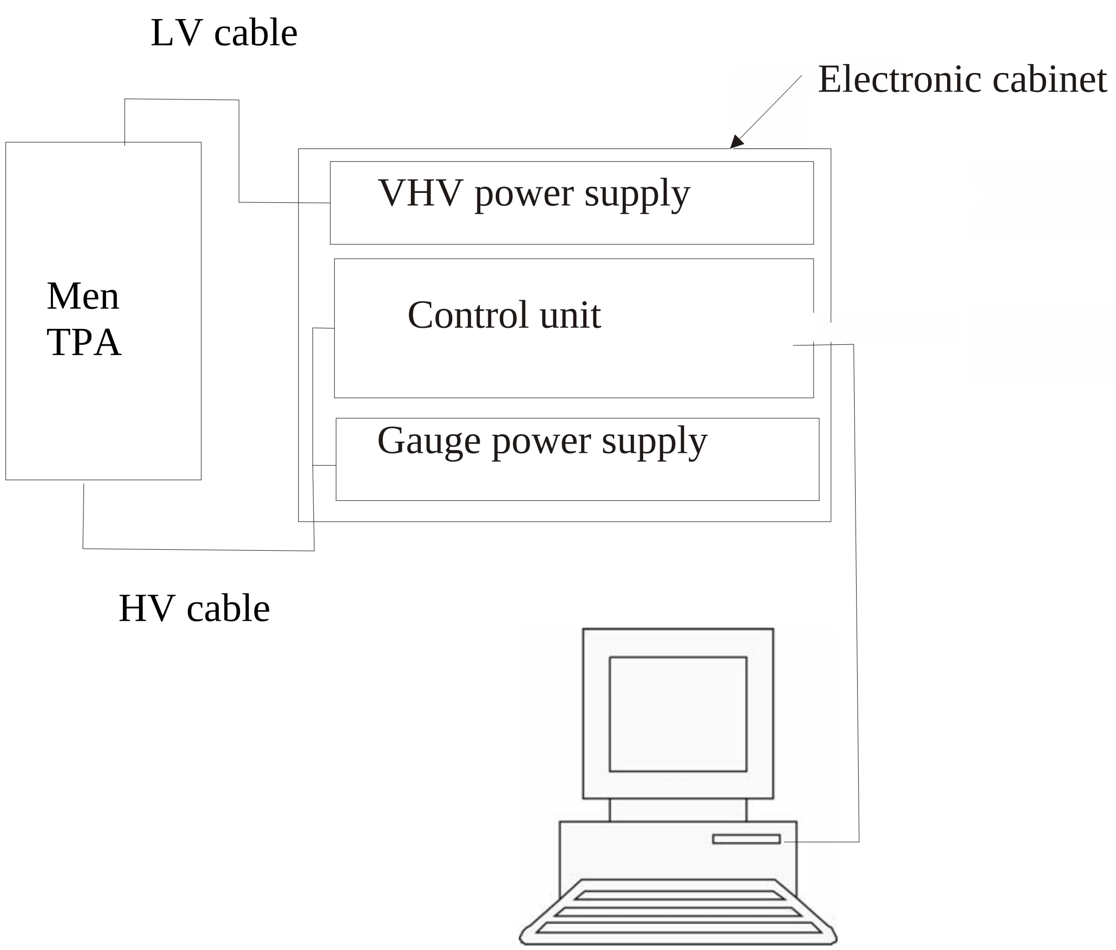


Fig. 2 The Neutron Generator functional components.

The MEN TPA contains the vacuum chamber in which the Alpha Particle Tracker should be embedded.

4.1.2 Functionalities

The Neutron Generator is considered as a unique functional system that controls the Neutron emission

The Neutron Generator should be operated with an external computer only.

The neutron emission should be controlled by changing the average beam current and the Target voltage. The nominal point of operation (100 kV and ~300 µA) and the continuous emission mode should be considered to produce 14 MeV neutrons at the typical value of:

10^8 n/s/4 π steradiant

for more of 2000 h of operation with stability of better than 10 % .

Adjustment of the neutron emission can be made by tuning the Very High Voltage power supply and the pressure in the tube.

<u>Very High Voltage</u>

Adjustable from 2 to 110 kV in steps of 0.1 kV (useful range for the neutron emission from 80 to 110 kV)

<u>Pressure</u>

The pressure inside the neutron generator should be adjusted by means of a gas replenisher current control and a pressure measurement gauge built into the tube.

<u>Tube current</u>

The tube current is measured between 0 to 0.5 mA in steps of 1 µA.

Full technical specifications of the **neutron generator** have been described in a report produced by SODERN (“Genie TPA technical specifications”). Basic requirements for the neutron generator control module are reported in the document ID2.3 Information system functional specifications .

4.1.3 Main interfaces

The main interfaces are :

a. mechanicals : neutron module with NRAN
cabinet with the
b. electrical (main power, ground)
c. control interfaces : the generator is operated by a software implemented in the Information System

d. safety interfaces : safety loop and locks to be implemented in the Information System

4.2 The Alpha Particle Tracker

Scope: to detect the associated alpha particles inside the Neutron Generator and define the tagged neutron beams.

This module can be considered split in 3 functional parts:

a) The YAP:Ce scintillator Hodoscope
b) The optical flange
c) The external read-out system

The YAP:Ce scintillation Hodoscope should be made of 64 independent small scintillation crystals, mounted in a matrix of 8 x 8. Typical dimension of each crystal is on the order of 5.8 x 5.8 mm to match the geometry of the external read-out PMT.

Scope of the YAP:Ce scintillation Hodoscope: to stop the associated alpha particles and convert their kinetic energy in a light signal.

Functional requirements of the YAP:Ce scintillation Hodoscope:

a.1 All crystals should be optically isolated to minimize cross talk
a.2 The crystals are protected from scattered deuterons and by internal UV light by using a suitable thin metal foil deposited by evaporation.
a.3 The thin metal foil should act also as a light reflector to maximize the light output

All components and materials employed in the preparation of the YAP:Ce scintillation Hodoscope should comply with the requirements of the Neutron Generator manufacturer.

The Optical Flange constitutes the interface between the high vacuum environment of the Neutron Generator with the embedded YAP:Ce scintillation Hodoscope and the external environment. The Optical flange should be prepared starting from a High Vacuum grade Stainless Steel DN 100 CF flange. The optical glass window should be brazed directly to the stainless steel employing materials that comply with the requirements of the Neutron Generator manufacturer.

Scope of the Optical Flange: to transmit the scintillation light outside the neutron generator to the external read-out system.

Functional requirements of the Optical Flange :

b.1 The glass window should be made of material so that it optimizes the transmission of the scintillation light.
b.2 The thickness of the glass window should be optimized in order to guarantee vacuum tightness and minimum optical dispersion of the scintillation light.
b.3 The glass window should be placed at a typical distance of 150 mm from the surface of the target in the Neutron Generator

The external read-out system allows the light pulse from the scintillation to be converted in a fast electrical signal ready to be handled by the front-end electronics. This task should be performed by a fast compact Photo Multiplier Tube (PMT) of multi-anode type that matches the geometry of the scintillation array.

Scope of the External Read-out System: to convert the scintillation light in an electrical signal outside the neutron generator ready for the front-end electronics.

Functional requirements of the External Read Out system :

c.1 The anode structure of the PMT should allow the read-out of the 8 x 8 matrix of the scintillator array embedded inside the Neutron Generator.
c.2 The PMT should have a typical gain of 10^6 with standard dark current at operating voltage about 1 kV.
c.3 The PMT should allow to perform time as well as energy measurements of the single light pulse by using standard front-end electronics.
c.4 The PMT should handle count rates as high as 25 kc/s on every single anodic line.
c.5 The working voltage of the PMT should be adjustable from 100 to 1500 V to allow the determination of the optimal operating conditions.

General functional requirements of the Alpha Particle Tracker:

1) The tagged neutron beam axis should be in a plane parallel to the Inspection System floor and perpendicular to the cargo container lateral walls.

2) About 1 % of the neutrons produced by the Neutron Generator should be tagged by using the alpha particle tracker.

3) The cross section of the neutron beam tagged by a single pixel of the tracker should not exceed about 20 x 20 cm^2 [FWHM] in a position corresponding to the center of an empty cargo container.

4.3 Detector Arrays

As shown in Fig.1, 3 detector arrays are used in the TNIS:

a) The Reflection Array, made of 4 high efficiency NaI(Tl) scintillators placed close to the neutron generator;
b) The Transmission Array, made of 5 high efficiency NaI(Tl) and one specialized neutron detector placed on the opposite side of the neutron generator, around the axis of the tagged beam;
c) The TOP Array made of 7 high efficiency NaI(Tl) scintillators placed on top of the cargo container.

Scope of the Detector Arrays:

Detection of the gamma-rays produced during the irradiation of the cargo container in coincidence with any of the Alpha Particle Tracker pixel detector. The analysis of the gamma-ray spectra um of the detectors will provide information about the elements inside the cargo container. High efficiency NaI(Tl) scintillators should be used for the detection of gamma-rays.

The neutrons transmitted through the cargo container in coincidence with a given specialized pixel of the Alpha Particle Tracker detector should be used to determine the profile of the tagged neutron beam inside the cargo container and provide a feedback to the operator.

General functional requirements of the Detector Arrays:

1) The reflexion array is embedded in the RDAN with the neutron module

2) The Reflection Array and Transmission Array should be movable along the vertical position to allow the scanning of any position of the cargo container from the bottom to the top positions (about 2.4 m). The distance between these two arrays and the cargo walls should be not larger than 30 cm when the inspection is performed.

3) The TOP array should be movable along the horizontal position to allow the scanning of any position of the cargo container in between the two lateral walls (about 2.4 m). The distance between these the TOP array and the cargo top surface should be not larger than 30 cm when the inspection is performed.

4) Movements of the detector arrays should be made by stepping motors. The position precision should be on the order of $\pm$1 cm.

5) The NaI(Tl) detectors of the Reflection Array should be shielded from direct neutrons emitted by the Neutron Generator by using suitable heavy metal screens (the thickness will be defined in Zagreb by the NaI irradiation tests). Due to the possible overlap of the useful gamma events and scattered neutron events in the NaI(Tl) detectors, in the time spectra, it is necessary to keep the possibility to modify the position of the reflection detectors (and associated shields) with respect to the neutron generator. A three axis movement is foreseen. The optimization of the position will be performed during the calibration tests and then the detectors and shields will be fixed in the appropriate position for the use of the TNIS during the EURITRACK Demonstration phase.

6) Some of the NaI(Tl) detectors of the TOP Array should be mounted in a lead collimator block, as shown in Fig. 3. Typical collimator of a single detector should be a right cylinder, 65 cm long with 16 cm internal and 26 external diameter, mounted with its axis perpendicular to the cargo top surface. Each NaI(Tl) scintillator should be placed in two different positions (corresponding to high or low collimation). The selection between the two positions should depend on the type of the cargo to be inspected, more precisely on the contrast between the material inside the cargo and the type of hidden material to be searched for.. The position precision should be on the order of $\pm$1 cm.

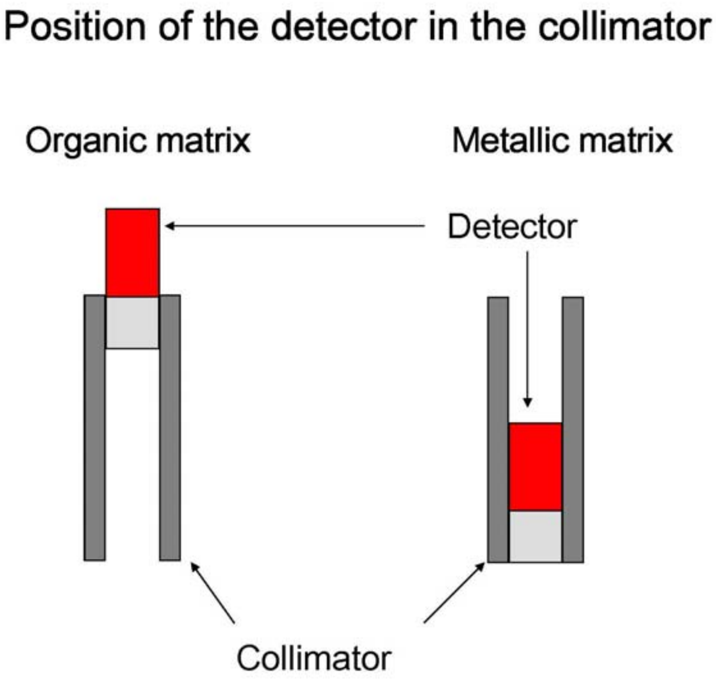


Fig. 3

7) The NaI(Tl) detectors of the Transmission Array should be mounted with the central detector in the tagged neutron beam axis, inserted in a lead collimator block similar to the one used for the top detectors (same axis as the tagged neutron beam), surrounded by the other four without collimator. . The central NaI(Tl) scintillator should be placed in two different positions (in front of or behind the collimator). The selection between the two positions should depend on the type of the cargo to be inspected , more precisely on the contrast between the material inside the cargo and the type of hidden material to be searched for. The position precision should be on the order of $\pm$1 cm.

8) Each NaI(Tl) detector should be optimized for the detection of gamma-rays in the energy range from $E\gamma$= 0.5 - 7 MeV. Time and energy determination of the detected gamma-ray should be performed with state-of-art performances. The detection efficiency should be optimized by using scintillator crystals having right cylinder shapes with dimensions 12.7 cm x 12.7 cm. The scintillation light should be converted in an electric pulse by using standard fast PMT directly coupled to the scintillator crystal. The PMT should have a typical gain of 10^6 with standard dark current at operating voltage about 1 kV.

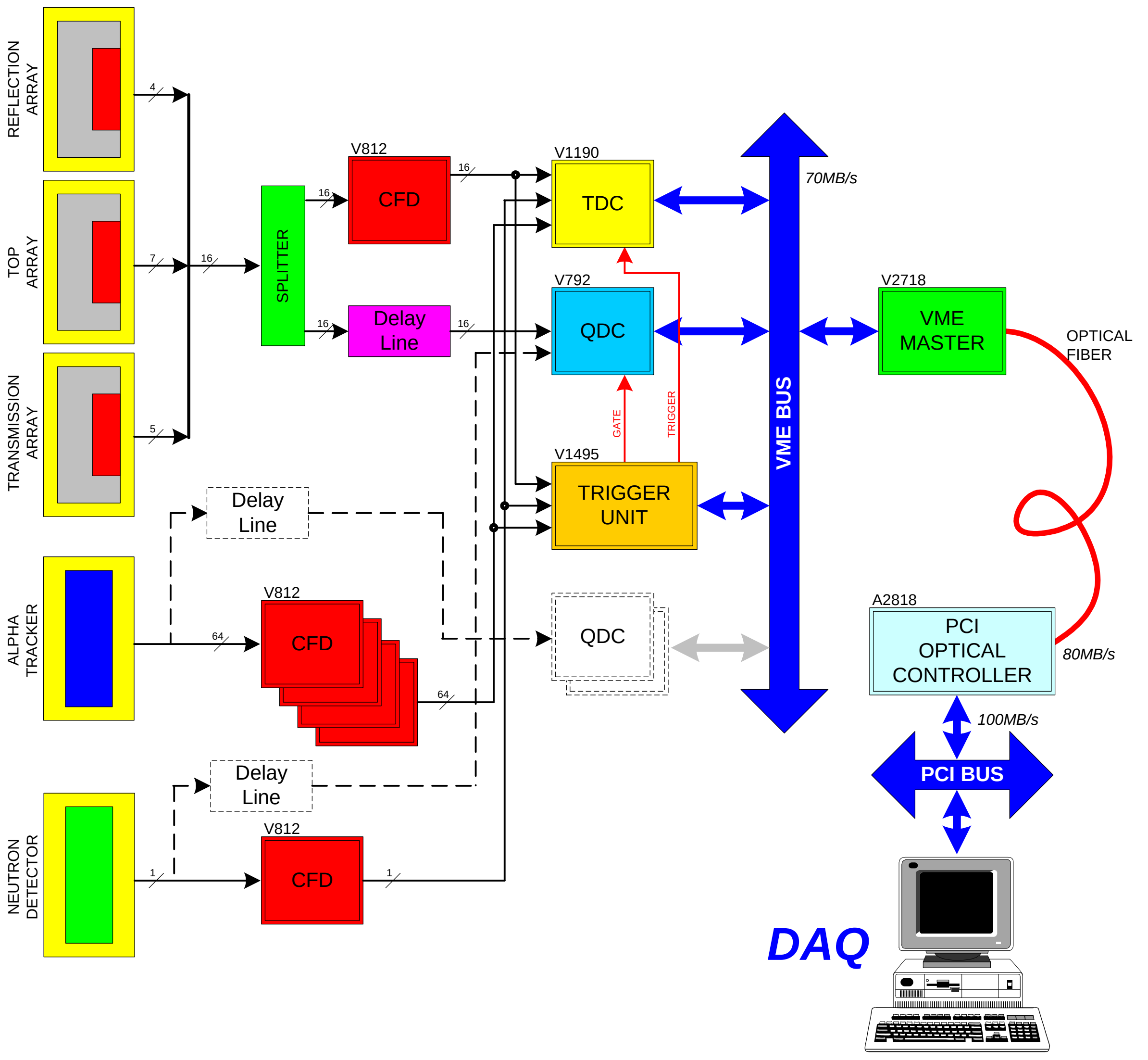
9) The NaI(Tl) PMT should allows to perform time as well as energy measurement of the single light pulse by using standard front-end electronics. The PMT should handle count rates as high as 150 kc/s. The working voltage of the PMT should be adjustable from 100 to 1500 V to allow the determination of the optimal operating conditions.

10) The specialized neutron detector should be mounted in the external ring of the Transmission Array detectors. The use of a lead shield ring to minimize the background noise induced on the gamma detectors by the C contained in this organic scintillators has to be studied during tests in Zagreb.

11) The specialized Neutron detector should employ a standard liquid scintillator cell with fast PMT read-out. Dimension of the Neutron scintillator cell should be on the order of 10 cm diameter x 10 cm thick to assure a good detection efficiency for 14 MeV neutrons. Neutron-gamma discrimination should be performed by using both the time-of-flight and the pulse shape discrimination techniques. The PMT of the neutron detector should handle count rates as high as 20 kc/s. The working voltage of the PMT should be adjustable from 100 to 2500 V to allow the determination of the optimal operating conditions.

4.4 FRONT-END electronics & Acquisition System

Scope: to provide the power supply and allow the management of all detector signals, including storage and retrieval of all events.



The FRONT-END electronics & Acquisition System is composed by 3 main hardware subsystems:

- The Power Supply System (PSS);
- The Front-End electronic system (FE);
- The Data Acquisition system (DAQ);

Scope of the PSS: Supply the voltage for the front-end electronics boards and the voltage divider of the photomultipliers.

Functional requirements of the PSS:

1) 16 independent lines for powering the NaI(Tl) PMT independently adjustable in the voltage range 0-4 kV (positive or negative) with a typical ripple of 30 mV-PP. The current full scale range can be 2mA or 0.2mA, having 20nA or 200nA set/monitor resolution respectively.
2) one independent line for powering the Alpha Particle Tracker PMT with the same characteristics described at 1).
3) one independent lines for powering the Neutron Detector with the same characteristics described at 1).

4) The PSS should be remote controlled by the EURITRACK Information (for example via an OPC server) and the embedded software should provide auto-check functions of the system and alarms in case of failures.

5) All PSS boards are housed in a 19” wide, 770mm depth, 4U high EURO mechanics Rack

6) The PSS boards have connectors type SHV and are connected to the PMT using proper cables.

CAEN’s candidate products are one SY2527 + two A1833 (or A1733)

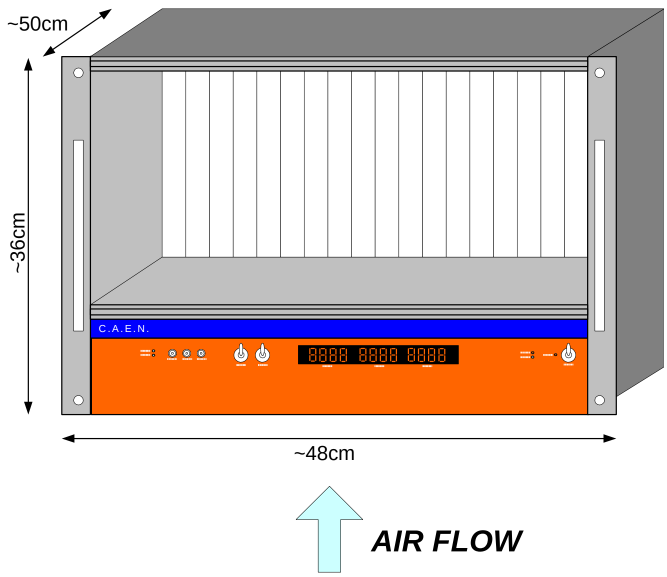
Scope of the FE: Process all PMT signals from the detectors, perform the required coincidences between any pixel of the Alpha Particle Tracker and any gamma-ray (or Neutron) detectors, digitize energy and time measured quantities.

Functional requirements of the FE:

1) 16 independent lines for processing the NaI(Tl) PMT signals. Each line should include a passive or active splitter, a Constant Fraction Discrimination (CFD) unit for fast timing and a 12 bit Charge-to-Digital converter (QDC) for energy determination.
2) 64 independent lines for processing the Alpha Particle Tracker anodic signals. Each line should include a Constant Fraction Discrimination (CFD) unit for fast timing and, optionally, a Charge-to-Digital converter (QDC) for energy determination.
3) 1 independent line for processing the Specialized Neutron Detector signal, including a Constant Fraction Discrimination (CFD) unit for fast timing and a Charge-to-Digital converter (QDC) for energy determination and Pulse-Shape discrimination module.
4) All FE components should be powered inside a standard VME crate.
5) CFD specifications: VME modules having at least 16 Channels per unit; Thresholds individually programmable with 1mV resolution; Programmable output width. Max jitter = +/-400ps. (CAEN’s candidate product is V812)
6) QDC specifications: VME modules having at least 32 Channels per unit; 12 bit resolution; 0 ÷ 400 pC input range; 100fC LSB; max 7 µs conversion+clear time. (CAEN’s candidate product is V792)

7) Time-of-flight measurements should be performed by using Time to Digital Converters (TDC): VME modules having 64 channels per unit; 100ps LSB resolution; 50us full scale range; 5ns double pulse resolution; deadtimeless multihit TDC. (CAEN's candidate product is V1190A)
8) The delay line can be realized by using cables with particular length. The maximum delay should be about 100ns.
9) The trigger unit must receive the outputs of the CFD boards and find proper coincidence between the lines from the Alpha Tracker/Neutron Detector and the Gamma detectors. This can be done in an user programmable FPGA with at least 81 inputs (ECL) and 2 outputs (one for the TDC trigger and the other one for the QDC gate. The board must be able to generate pulses of programmable duration. (CAEN's candidate product is V1495)
10) All the VME boards in the crate are controlled by a VME master that must be able to interface the DAQ via an optical link and a PCI board. The VME to PCI bridge should sustain a transfer rate of about 50MB/s. FE embedded software should provide auto-check functions of the system and alarms in case of failures. (CAEN's candidate product are one V2718 + one A2818)
11) One VME64 crate (21 slots) with power supply (+5V, +12V, -12V).

12) All Front End boards (except for the delay lines) are housed in a standard VME64 19" wide, ~500 mm depth, 8U (about 36cm) high EURO mechanics Rack. The crate include fan units for ventilation and it is necessary to leave open the bottom side of the carte to allow the air flow.



13) The signals from the detectors are connected to the splitters, CFD and QDC boards with 50 ohm coaxial cables and LEMO connectors. The outputs of the CFD are connected to the TDC and the Trigger Unit using 34 wire flat cables.