Qualification of the Industrialized Libera MONACO 3 Digital Acquisition System dedicated to Fission/Ion Chamber Measurements in Research Reactors

Loic Barbot[1], Gregoire De Izarra [1], Christophe Destouches[2], Danilo Bisiach[3], Manuel Cargnelutti[3], Sebastjan Zorzut[3], Matjaž Škabar[3], Aleš Bardorfer[3], Aurora Makovac[3], Jure Trnovec[3], Peter Paglovec[3]
[1]CEA, DES, IRESNE, DER, Instrumentation Sensors and Dosimetry Laboratory, France
[2]CEA, DES, IRESNE, Reactor Studies Department, France
[3]Instrumentation Technologies, Slovenia
loic.barbot@cea.fr - danilo.bisiach@i-tech.si

***Abstract*— The CEA Sensor, Dosimetry and Instrumentation Laboratory (LDCI) has been working since 2011 on an integrated acquisition system called MONACO, '*Multichannel Online Neutron Acquisition in Campbell mOde*', for fission chamber measurements. Taking into account the feedback acquired up to the CEA TRL7 version, the LDCI Lab and the Instrumentation Technologies company (Solkan – Slovenia) initiated in 2020 a two years collaboration agreement to build the Libera MONACO 3 industrialized version required for reactor use and mass production. After a final qualification performed in the Slovenian TRIGA Mark II reactor in March 2023, the system will be available on the nuclear instrumentation market by the end of 2023.**

Keywords — Fission Chamber, Ion Chamber Digital Acquisition System, Neutron Flux, Pulse Mode, Campbell Mode, Current Mode.

I. Introduction

THE CEA Sensor, Dosimetry and Instrumentation Laboratory (LDCI) has been developing since 2011 an integrated acquisition system called MONACO which stands for *'Multichannel Online Neutron Acquisition in Campbell mOde*' for fission chamber (FC) measurements. The spread use of such online detectors were suffering from the lack of up-to-date and integrated signal acquisition system on the nuclear instrumentation market. While building its new Jules Horowitz Reactor (JHR), CEA was seeking a maintainable and standardized measurement system.

The MONACO system is unique as it integrates all the required features in one module to find out optimum parameters for FC operations and calibration prior to absolute online measurements. This module is also unique as it makes accessible the overlapping analysis of FC operating modes using a sole acquisition system.

The LDCI Lab and the Instrumentation Technologies company (Solkan – Slovenia) agreed in 2020 on a 30 months collaboration to develop the MONACO 3 version with a maximum level of technological maturity as well as all validations and certifications required for reactor use and mass production.

This joint development is based on the existing Instrumentation Technologies digital board, called Libera Digit 500, taken as-is. This also includes a fully redesigned electronic architecture, a redeveloped firmware containing all the data processing algorithms including the implementation of a true PHA acquisition mode, an innovative development for current measurement electronics with an improved bandwidth of 0 to 1 kHz and a new graphical user interface development carried out by Instrumentation Technologies based on the CEA existing interface.

After comprehensive lab test series with synthetic signals to ensure overall operation and performances, the two MONACO 3 prototypes completed a final qualification performed in the TRIGA Mark II reactor at the Jožef Stefan Institute (Ljubljana – Slovenia) in March 2023, using CEA made miniature fission and ion chambers.

The "Libera MONACO 3" version will be available on the nuclear instrumentation market by late 2023. It is meant to ease the implementation of fission and ion chambers as part of in-core instrumentation, gathering all required data acquisition systems in one with four channels, encouraging multiplication of neutron flux core mapping and neutron/gamma field characterization of experimental locations in research reactors.

II. Context

Fissions chambers (FCs) are online neutrons detectors widely used in nuclear reactors, often as part of the reactor command control system. In this case, FCS are commonly excore massive detectors with a strong sensitivity to neutrons and operated in pulse mode for reactor start-up measurements. They are frequently part of a displacement device for nominal power measurements while used in current mode. Both pulse and current mode acquisition electronics used in command control systems are specifically validated for nuclear safety, obeying the 2 out of 3 logic as safety rule and with a strict usage dedicated to the reactor operation and fixed automatic data processing.

Based on the same gaseous/ion detector technology, CEA developed from the 1960s some miniature (Ø3 mm) and subminiature (Ø1.5 mm) fission chambers [1] with a mineral integrated cable for incore neutron flux measurements in research reactors. These FCs are deployed in reactor core for local neutron measurements close to irradiation locations. Using dedicated FC calibration methods [2] made absolute neutron flux measurements achievable. It is also possible to get neutron spectrum with spectral indices techniques, miniature FC sensitivity being easily adapted to a neutron energy range with appropriate fissile coatings. These FCs are often used either at low neutron flux range in zero-power reactors [3] in pulse mode or at high neutron flux range in material testing reactor in current mode using both dedicated acquisition systems mainly derived from command control systems.

With the start-up of new research reactors such as the Jules Horowitz Reactor (JHR) at CEA Cadarache, miniature FCs are expected to be part of most instrumented experimental devices for technological irradiations or neutron field characterization. FCs will play the role of local neutron flux monitors giving access to online accurate neutron flux levels/spectra over a wide reactor power range, during either stabilized or transient reactor operations. This more intensive use of FCs requires new FC acquisition systems with enhanced performances.

Such experimental constraints for neutron flux measurement were first met at CEA, within the bilateral collaboration project with ANSTO (Australia), during the preparation of the neutron flux mapping of fuel coolant channels of the OPAL reactor [4]. Based on the previous CEA IRINA (Instrumentation RES Interne Neutronique Automatisée) project initiated in 2002 [5], the CEA LDCI Lab launched in 2011 the development of an integrated acquisition system in support to FC comprehensive measurements, called MONACO (Multichannel Online Neutron Acquisition in Campbell mOde) [6]. From the beginning, the MONACO system was designed to perform FC measurements over several decades of neutron flux, being capable of running FCs in both pulse and current modes as well as in the intermediate mode, called Campbell or fluctuation mode.

In the 2011-2019 period, the LDCI Lab, along with the CEA LIST Sensors and Electronics Lab (LCAE) worked on various implementations of the MONACO system, ending up in 2019 to the MONACOv2 TRL7 version in 2019 [7, 8]. This multichannel acquisition system, dedicated to neutron (and gamma using ion chambers) measurements was unique as it was integrating all the following features for FC measurements in one module: automatic generation of saturation curves, automatic generation of pulse discrimination curves, detector pulse characterization using the embedded oscilloscope module, pulse mode acquisitions in count rate or pulse height analysis, fluctuation mode and current mode acquisitions. FCs plugged to a single connector and the implemented operating modes run constantly in parallel, with a minimum acquisition time of 1 ms.

Taking into account the expertise and feedback acquired during CEA labs development, the LDCI Lab and the Instrumentation Technologies company (Solkan – Slovenia) initiated in 2020 a 30 months collaboration agreement to build the Libera MONACO 3 industrialized version.

III. Libera MONACO 3 Design and Performances

The following sections provide an overview of the key components of the Libera MONACO 3 system. The instrument's main blocks are described in the schematic diagram illustrated on Fig. 1.

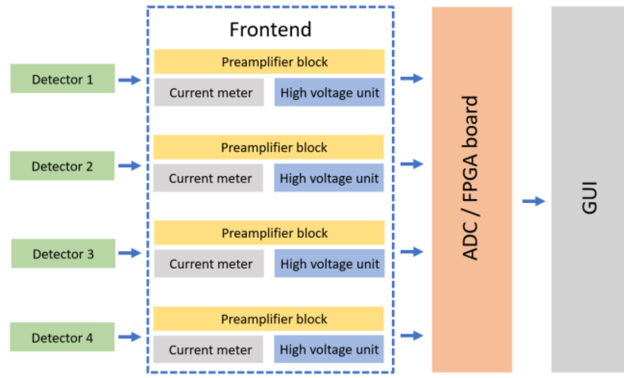

Fig. 1. Libera MONACO 3 block structure description.

The signals at the outputs of the detectors are received through 4 separate HN connectors. These signals are subsequently directed into a frontend consisting of a transimpedance preamplifier block [9], a current meter unit, and a High Voltage (HV) unit. A digitizer unit, based on the Libera Digit 500 DC (developed by Instrumentation Technologies), is acquiring the data, is performing digital signal processing (DSP), and is transmitting the acquired data to a graphical user interface (GUI) running on a local computer.

A. Front end

The frontend is described in Fig. 2:

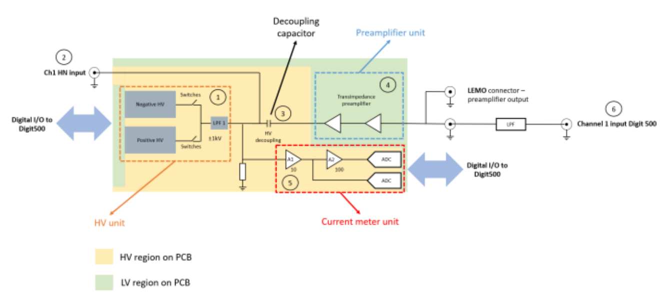

Fig. 2. Libera MONACO 3 frontend block description.

The current signal entering the HN input connector undergoes decoupling from the HV component using a capacitor. Within the transimpedance preamplifier, the current signal is amplified and converted into a voltage signal. The amplifier has a total bandwidth greater than 20 MHz and a maximum output noise of 40 mVpp when connected to an instrument output with a cable having a total capacitance exceeding 8 pF. The transimpedance gain of the preamplifier is approximately 3100 V/A.

A high voltage block is providing both negative and positive high-voltage polarization within the range of -1 kV to +1 kV, with a maximum precision of 1% on the target value. The total ripple in this block falls within the range of 50 mV.

The current measurement unit is designed to measure the current supplied to the detector and can operate in two separate ranges:

- The high gain range spans from 0 nA to ±10 uA.
- The low gain range spans from 0 to ±1 mA.

Both range measurements run concurrently, utilizing two separate ADCs with a sampling rate of 1 kS/s each for precise current measurement and integration of lower currents.

The high voltage and current measurement blocks on the frontend boards are controlled through an I/O bus interface that is directly connected to the FPGA on the digitizer.

B. *Digitizer unit*

Four Analog Digital Converters (ADC) on the Libera Digit 500 DC unit convert the four output signals from the transimpedance amplifiers into digital form. The ADCs operate at a sampling frequency of 491.52 MS/s, offering a resolution of 14 bits and a noise floor of 90 dB. Within the analog RF chains, there are user-controllable variable attenuators with a range of 31 dB. These attenuators are used to control the input signal intensity and to enhance the overall dynamic range of acquired pulses.

The digitized data are then transmitted to the Xilinx 7035 System On Chip (SOC) unit, which integrates both the Field Programmable Gate Array (FPGA) and the Advanced Risc Machine (ARM) processing unit. The data acquisition trigger enables the storage of data in the memory buffer chunk, while parallel Digital Signal Processing (DSP) calculations are performed simultaneously.

C. *DSP*

The DSP chain incorporated within the digitizer unit is depicted by the blocks illustrated in Fig. 3.

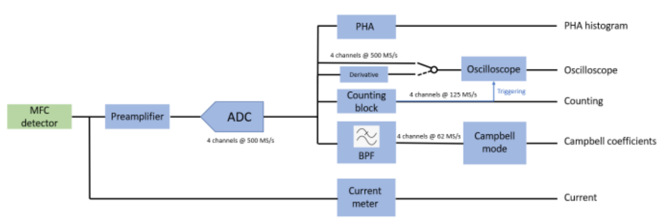

Fig. 3. DSP block schematics.

The DSP block, implemented within the FPGA, encompasses various sub-blocks that serve different functions:

- Pulse Height Analysis (PHA): this block computes the charge associated with the pulse population and presents data as a histogram. It also includes a pile-up rejection mode.
- Oscilloscope: this block is acquiring and visualizing pulse signals. It functions as an oscilloscope, allowing the user to monitor and collect pulse signals.
- Counting mode block: this block is dedicated to pulse discrimination and counting. Individual pulses are counted when their amplitude exceeds a predetermined threshold. The output of the counting block is a Count rate in counts per second (Cps). The implemented counting method employs high-pass filtering in conjunction with a Schmitt trigger. This approach enables low dead time and reduced sensitivity to pile-up while maintaining a lower signal-to-noise ratio (SNR).
- Campbell mode block: the acquired ADC data pass through a bandpass filter with a frequency range of 400 to 800 kHz and a data rate of 61.44 MHz. Subsequently, the K2, K3, and K4 coefficients are calculated.
- Current meter: the data recorded by the current meter block in the integrated frontend is transmitted to the LD500 digitizer via the SPI bus.

D. *GUI*

The GUI serves as primary user interface through which the operator can access and acquire data from the detectors. It utilizes Python 3.10, PyQT4 graphic framework, and runs on Windows 10™. A screenshot example of the GUI is shown on Fig. 4.

Fig. 4. Libera MONACO 3 GUI screenshot example.

The GUI development is built upon the ergonomic principles of the previous MONACOv2 system, and it incorporates additional modules to perform statistical analysis and calculations on the acquired data.

The communication infrastructure with the Libera Digit 500 unit operates over Ethernet and utilizes an HTTP adapter, enabling the exchange of large volumes of compressed data as streams of binary data.

In Fig. 4, the left hand part displays plots of the signals from the four channels, which consist of counting mode, fluctuation mode, and current modes. Data decimation can be adjusted by the user, allowing for a maximum resolution of 1 ms. For long-term reactor campaigns, data acquisition can be performed with reduced data rates.

The GUI integrates essential functions for instrument control, including:

- High voltage adjustment for the detector polarization,
- Automatic threshold discrimination curve,
- Automatic saturation (HV) curve ,
- Parameter settings for DSP functions.

IV. Qualification

Libera MONACO 3 qualification was completed through reactor tests carried out during 2 days in early March 2023, in the Slovenian TRIGA Mark II reactor. The fully characterized irradiation conditions helped to validate the fully operability of the Libera MONACO 3 in representative neutrons and gamma flux conditions.

A. *TRIGA Mark II Reactor*

The JSI TRIGA Mark II reactor is a pool type research reactor (250 kW – first criticality in 1966) cooled by natural water convection. The uranium zirconium-hydride fuel mixture designed by General Atomics has unique properties that make the reactor inherently safe and suitable for training, research and isotope production. The JSI reactor division and the LDCI Lab have a 15 years collaboration in radiation measurements and instrumentation qualifications [10], which helped to fully characterize different experimental locations within the TIGA Mark II reactor.

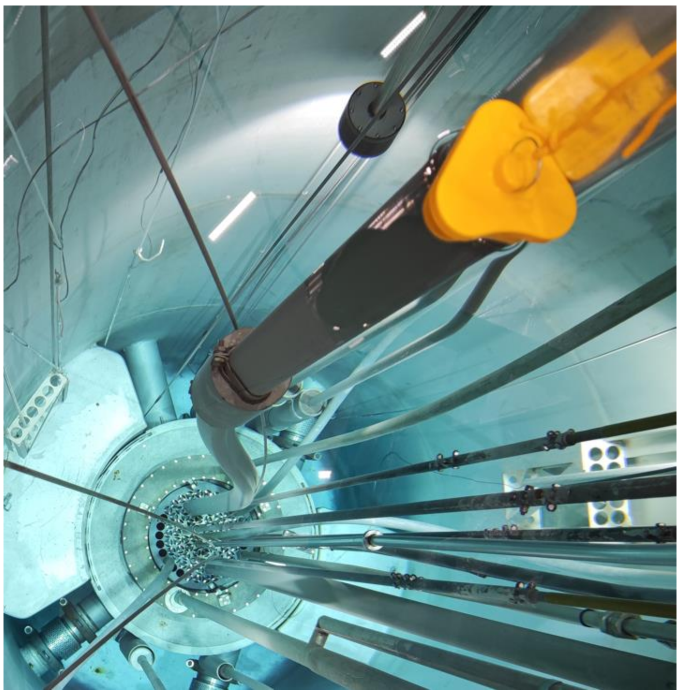

Fig. 5. Photograph of the JSI TRIGA Mark II reactor pool

B. *Experimental Set-Up.*

The full range of the three operation modes of the Libera MONACO 3 system were qualified thanks to two CEA Ø3 mm miniature FCs (respectively with 10 µg of uranium-235 and 100 µg of uranium-238) placed incore in the MP17 and MP25 central locations. The current mode upper range was confirmed using one Centronic (Croydon, UK) FC (0.165 g of uranium-235) usually used for excore measurements, kindly loaned by JSI, and placed in the reactor triangular channel (yellow cap on Fig. 5).

In complement, a CEA Ø3 mm miniature ion chamber and a rhodium emitter SPND were deployed to confirm the possibility to use Libera MONACO 3 with such detectors.

C. *Reactor Tests*

The TRIGA reactor was operated with several stabilized power steps from 0.1 W to 250 kW. Libera MONACO 3 operating modes were successfully tested with the following results:

- Pulse mode linearity is demonstrated up to 3.10^6 $c.s^{-1}$; it should be extended to $>1.10^6$ $c.s^{-1}$ providing a fine-tuning of pulse mode parameters.
- Campbell mode is verified to be linear over more than 5 decades of neutron flux.
- Current is confirmed operational within the target 1 nA – 1 mA current range (See Fig. 7).

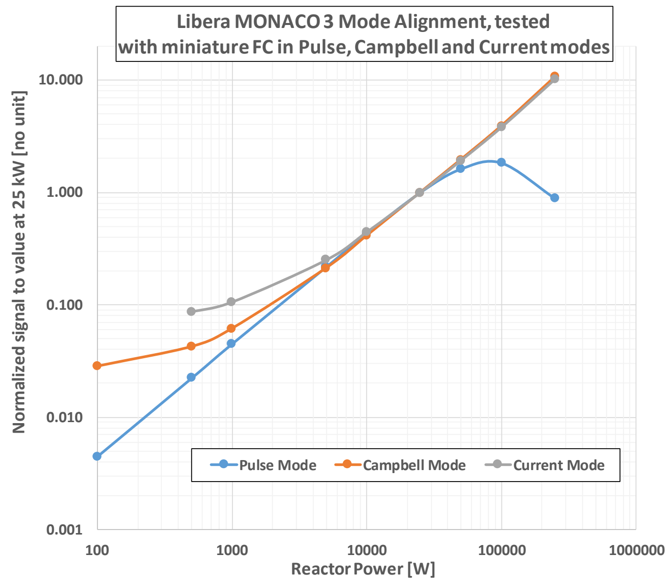

Fig. 6: Tests results of the Libera MONACO 3 mode alignment, using CEA miniature U235 FC.

As it was one of the most challenging part of this industrialization process, Fig. 7 is a focus on the current mode. Thanks to an artificial "reactor power equivalent U235 fission rate" x-axis, CEA U235 miniature FC and Centronic FC measurements are plotted on the same graph; presented here along with IC, Rh SPND and Keithley electrometer currents, the latter taken here as reference.

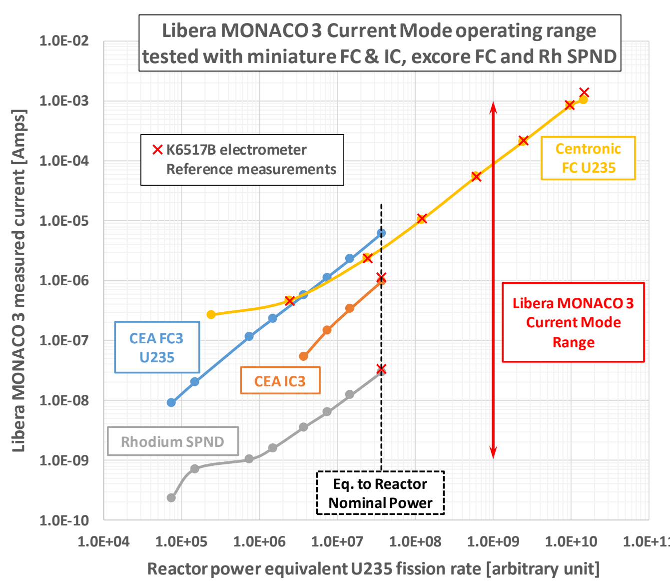

Fig. 7: Tests results of the Libera MONACO 3 current mode range, using CEA FC and IC, Centronic FC and a Rh SPND.

The 1 nA – 1 mA current range is highlighted in red on Fig. 7, its linearity is validated using the two different FC measurements as well as current absolute values in comparison to the electrometer measurements. Fig. 7 also shows the possible use of Libera MONACO 3 with IC detectors and even with SPNDs (HV set to 0 V) which confirm the versatility of the system for different kind of reactor measurements.

V. Conclusions

The Libera MONACO 3 system will be available on the nuclear instrumentation market at Instrumentation Technologies by the end of 2023.

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