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Online / Offline reconstruction of trigger-less readout in the R3B experiment at FAIR

Dmytro Kresan, Mohammad Al-Turany and Florian Uhlig
GSI Helmholtzzentrum für Schwerionenforschung mbH, Planckstrasse 1, D-64291 Darmstadt, Germany
E-mail: d.kresan@gsi.de, m.al-turany@gsi.de, f.uhlig@gsi.de

Abstract. The R3B (Reactions with Rare Radioactive Beams) experiment is one of the planned experiments at the future FAIR facility at GSI Darmstadt. R3B will cover experimental reaction studies with exotic nuclei far off stability, thus enabling a broad physics program with rare-isotope beams with emphasis on nuclear structure and dynamics. Several different detection subsystems as well as sophisticated DAQ system and data-analysis software are being developed for this purpose. The data analysis software for R3B is based on FairRoot framework and called R3BRoot. R3BRoot is being used for simulation and detector design studies for the last few years. Recently, it was successfully used directly with the data acquisition and for the analysis of the R3B test beam-time in April 2014. For the future beam times the framework has to deal with the free streaming readout of the detectors. The implementation within R3BRoot to fulfil this trigger-less run mode will be discussed in this paper, as well as the set of tools developed for the online reconstruction and quality assurance of the data during the run.

1. Introduction
Future FAIR (Facility for Anti-proton and Ion Research) is currently being built in Darmstadt, Germany and will host basic research for about 3000 scientists from 50 countries. It is a joint international effort of currently 10 member states. Research fields of experiments at the FAIR facility are Atomic and Plasma Physics; Compressed Baryonic Matter (heavy-ion collisions); Nuclear Structure, Astrophysics and Nuclear Reactions (NuSTAR) and Hadron Physics. The accelerator complex is the synchrotron SIS 100 with possibility to accelerate protons and heavy ions up to energy of 15 AGeV.
R3B (Reactions with Rare Radioactive Beams) experiment, as part of NuSTAR [1], is an international collaboration including about 50 institutes and covers broad physics program of experimental reaction studies with exotic nuclei far off stability, nuclear structure and dynamics, astrophysical aspects and technical applications. It is a fixed target experiment, operating in inverse kinematics mode, and is composed of complex detector sub-systems such as silicon tracker, gamma and proton calorimeter CALIFA (CALorimeter for In-Flight emitted pArticles), proton and heavy fragment tracking arms and neutron spectrometer NeuLAND (new Large-Area Neutron Detector). Super-conducting dipole magnet GLAD (Large-acceptance Dipole) will be used for measurement of charged particles momenta and for separation of protons and heavy fragments. It is a challenge to develop a dedicated online reconstruction and analysis software, which has to handle sophisticated Data Acquisition System and trigger-less operation of mentioned detectors.
2. R3BRoot / FairRoot framework
The FairRoot framework [2] is developed at GSI and provides basic functionality for simulations, reconstruction and analysis of FAIR experiments. Implementation of I/O, simulation part, partially parameter handling and task mechanism are based on ROOT [3]. Additional format for parameter storage (e.g. ASCII) can be chosen at runtime. Experiment frameworks such as R3BRoot, CbmRoot and PandaRoot inherit basic functionality and implement detector-specific geometries, event generators, reconstruction and analysis algorithms and magnetic field handling (Figure 1). The code is compiled into shared libraries, which are loaded on demand, depending on the user-defined setup. The VMC (Virtual Monte Carlo) concept is used as interface to Geant3 and Geant4 transport engines in simulations. Concerning experimental data, multiple formats of input are supported and foreseen, e.g. Multi Branch System (MBS), developed at GSI.

**Figure 1.** Schematic layout of how R3BRoot inherits basic framework functionality from FairRoot and its core internal objects.

The R3BRoot framework was used as a simulation tool for feasibility studies performed within preparation of Technical Design Reports for R3B detector sub-systems. Due to the modular and generic design of FairRoot, already developed reconstruction and analysis algorithms can be now applied to experimental data. Such application took place in April 2014 during beam-time at SIS18 (GSI) with the NeuLAND prototype, where online operation of R3BRoot, connected to a remote event server [4], was tested. In addition, reconstruction and physics analysis of neutron detector measurements was performed in offline mode - using data files stored by DAQ system. As also shown in Figure 1, a single implementation of calibration and reconstruction routines is used in both cases: running with online stream and opening stored data files. FairRoot also provides a possibility to monitor pre-selected variables during running experiment. It is performed by a ROOT JavaScript application, which is encapsulated into HTML code.

Currently, active development is ongoing into the direction of distributed computing using message queues over the network [5]. This concept is realised within the ALFA project - joint ALICE and FAIR effort. R3BRoot will make use of this functionality, especially for delivering data to multiple monitoring clients.
3. Data flow

Data acquisition system of R3B sends the data using Multi Branch System (MBS) - entirely written in C, based on Real-time system LynxOS and with message oriented data flow via TCP/IP sockets (up to 10 Gbit) [6]. Data stream is formed by a sequence of events with a fixed-size event-header and a set of sub-events of variable length. Each sub-event corresponds to a detector and contains a header (with data type, DAQ parameters, message size), followed by measurements - raw hits. FairRoot framework takes over the communication with Remote Event Server or handling of data file(s), while experiment-specific R3BRoot classes (unpackers) decode detector sub-events and produce raw data output saved as ROOT objects. This data is then available for user-defined calibration, reconstruction and analysis tasks using I/O manager of FairRoot.

In April 2014 beam time the synchronised data stream was used, in which an MBS event corresponds to an interaction of beam with target (or alternatively signals from cosmic rays) and contains the main hardware trigger value, as well as the data recorded in all detectors. After unpacking such structure as explained above, the data was directly fed into reconstruction tasks (left picture in Figure 2).

![Figure 2](image)

**Figure 2.** Two different structures of data flow in R3B: left picture - event-wise structured stream with a hardware trigger (April 2014 beam time), right picture - asynchronous data stream based on time-stamps (October 2014 beam time). For the latter one an additional stage of event building was introduced in R3BRoot.

During the follow-up experiment, R3B has moved to the asynchronous data taking with several DAQ streams. In the latter case an MBS event contains data only from one detector, supplemented by a time-stamp value at which it was recorded. Events are coming with an arbitrary time delay and occur without any sequence (right picture in Figure 2). The hardware trigger value from the main DAQ is no longer relevant. Therefore an intermediate step - event building - was introduced before reconstruction algorithms. Its task is to synchronise data from the detectors depending on the provided time-stamps and its performance should be sufficient in order to run in the online mode. Moderate interaction rate of few hundred Hz with small amount of secondaries produced and low detector granularity do not require large scale computing cluster for online data processing, but can be rather implemented by a one-node solution, which is described in the following sub-section.
3.1. Online synchronisation

As mentioned above, the synchronisation task runs after the unpacking level - to operate with R3BRoot objects instead of binary raw data, and prior to reconstruction algorithms - for them to have access to structured events. Its functionality is implemented within a single functional class, supplemented by the required data structures. Online stitching is realised by buffering events from DAQ streams of different systems, according to the detector list configuration of the steering macro, and later by analysing the timestamp values of the buffered events. This R3B-specific event builder was designed according to I/O management scheme of FairRoot core classes and follows the general framework concept.

In the current application, as required by the October 2014 experiment, the synchronisation of the neutron detector (NeuLAND) and gamma calorimeter (CALIFA) was tested. The time pattern analysis algorithm relies on the DAQ system feature, which takes care of time sorting of a stream. An additional assumption was made, that the data from CALIFA would come later than from NeuLAND, but with arbitrary time delay, which corresponds to the current DAQ configuration. Figure 3 shows the time difference in [ns] between gamma calorimeter and neutron detector, for all event combinations from the buffer, as seen by the event builder. The peak around 350 ns corresponds to a true match, i.e. a reaction took place in the target, and gives a signal to produce an output event containing all the data. The exponential decay distribution starting at zero is due to random false combinations or background events, and these entries are ignored.

![Figure 3. Time difference (in nanoseconds) between sub-events from CALIFA and NeuLAND detectors in asynchronous data stream. Note logarithmic scale on Y-axis. Peak around ≈350 ns corresponds to matching of the events to real beam-target interaction. A range cut of 250 – 380 ns was applied to select the signal events.](image)

The code takes care internally, that the buffer is not overfilled with not matched entries, by removing those with obsolete time-stamp, allowing long-run stability. Average time delay value and its standard deviation might vary for different experiments, therefore the time window for true coincidences has been made a parameter to be set by a user. Two running modes, processing data with or without online synchronisation, were tested on a regular PC, and did not result in a noticeable performance change. Currently development is ongoing to include further detectors into the reconstruction scheme.

In the next sections of this paper we will focus on physics performance and results obtained from these two experimental runs. In particular, how CALIFA detector can be used as a beam interaction software trigger for the neutron spectrometer.
4. Experimental results
In this section we shortly describe major achievements of the very first application of the R3BRoot framework to online / offline data reconstruction in R3B experiments.

4.1. May 2014 run
With respect to R3BRoot software, the scope of R3B test experiment in May 2014 was to test the data taking of NeuLAND standalone in the online mode, and to perform, so called, near-line analysis in the offline mode, by adding reconstruction of the time-of-flight start counter. Experimental conditions: $^{58}$Ni beam at 700 AMeV on the liquid hydrogen target. The application of R3BRoot framework was successful in terms of multiple fixes and improvements of the frameworks code and R3B-specific calibration and reconstruction routines. In addition, the offline analysis has provided first physics results. Example of one of significant achievements is shown in Figure 4 and illustrates capability to distinguish between neutron and gamma hits in NeuLAND.

![Figure 4. Reconstruction of neutron detector (NeuLAND at R3B) data with the reference to time of start counter. Distribution of measured hit velocity as function of detector module index. Contribution from gamma rays, emitted from the target, are clearly separated and located in the bump below 29 cm/ns. Homogeneity along the X-axis indicates good quality of time calibration and synchronisation. This analysis is mandatory for the neutron identification.](image)

The separation is done by calculating the velocity of a hit assuming distance to the target and time-of-flight provided by the start counter. Gamma rays reach the detector with the speed of light, while incident neutrons keep moving with the beam velocity. At beam energy of 700 AMeV the time and position resolution of the detector modules is sufficient to make a sharp cut. As a future development, we plan to include this near-line analysis into online monitoring system, which will help to identify performance and hardware problems with the detector, occurring during the data taking, and thus react immediately.

4.2. October 2014 run
As was mentioned in the Section 3, during the second test experiment R3B has moved to the set-up with asynchronous data read-out, based on time-stamps. The NeuLAND prototype during this run had 4 times more scintillator modules (400 instead of 100), which allows for testing high-level physics reconstruction, previously developed on the simulated data (i.e. multi-neutron event identification [7]). Experimental conditions: $^{48}$Ca beam with 550 AMeV on a lead target. The purpose of the R3BRoot application in this experiment was an extended test of running with two detector systems (CALIFA and NeuLAND), which were read-out by two independent DAQ streams. The details on the algorithm used for synchronisation is described in Section 3.1.
The performance of the software trigger, which was defined as the presence of at least one hit in the gamma calorimeter, is shown in Figure 5. It was demonstrated, that the off-spill (or background) events can be strongly suppressed (by factor 100), while keeping the data containing physics interactions (efficiency of about 20%).

![Figure 5](image.png)

**Figure 5.** Illustration of gamma calorimeter (CALIFA at R3B) performing as the software trigger. Events with value 1 - on-spill, 2 - off-spill, 3 - system clock trigger (used for time calibration). Line histogram shows distribution before applying trigger, filled histograms - after. Effective background suppression with reasonable signal efficiency of $\approx 20\%$.

Figure 6 compares measured with NeuLAND energy loss spectra with and without the software trigger. Minimum-ionising peak to noise ratio becomes much higher, which speaks in favour of proper selection of events. More elaborated analysis of the R3B data requires precise high quality energy and position calibration of gamma calorimeter and is work in progress.

![Figure 6](image.png)

**Figure 6.** Spectra of uncalibrated energy loss per module measured with NeuLAND. Left picture - before applying CALIFA as software trigger, right picture - after. Peak of minimum ionising particles is at 400 QDC units. Strong suppression of low-energy background is shown.
5. Summary
The R3BRoot framework, developed since 2009, was successfully used to perform the simulations for demonstration of the feasibility studies of planned R3B physics program and for the design of detector systems. Reconstruction and analysis algorithms, verified with simulated data, can be now applied to experimental measurements. In two R3B test experiments, in May and October 2014 at the GSI accelerator facility, online data taking and monitoring as well as offline physics analysis were performed using the R3BRoot framework. This pilot application resulted in multiple fixes and improvements to the code and its performance. It has been shown, that R3BRoot is capable of handling experimental data, being powerful and flexible tool for the physics analysis.

The final goal is to fulfil requirements of the R3B Collaboration to the reconstruction and analysis software within the R3BRoot framework, to be able to take first full-scale physics data in 2017. Currently work is ongoing on adding support for all detectors of the set-up, in terms of event building in trigger-less mode, time synchronisation and calibration.

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