

# Modernized Experimental Setup KOLKHIDA Designed to Study the Interactions of Polarized Neutrons with Polarized Nuclei

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## Introduction

The experimental setup KOLKHIDA [1] has been designed to study the interactions of polarized neutrons with polarized nuclei, in particular to study the neutron nuclear precession (nuclear pseudomagnetism) [2]. The neutron nuclear precession is observed when polarized thermal neutrons pass through a target of polarized nuclei. The following is required for experimental study of this process:

- Spectrometer of polarized neutrons
- Polarized nuclear target
- Experimental setup control and operation system
- System for study of the process
- Experimental setup software

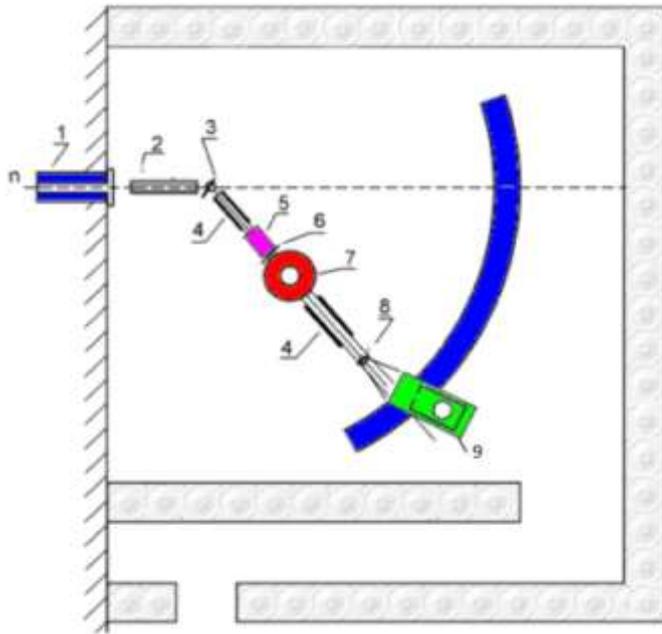
The experimental setup KOLKHIDA was built more than a decade ago and initially consisted of a polarized neutron spectrometer and a <sup>3</sup>He-<sup>4</sup>He dilution cryostat with superconducting solenoid. Recently the setup has been upgraded and equipped with an additional component, which allows us to extend its experimental capabilities. As a result of this modernization:

- we have upgraded the experimental setup control and operation system;
- the <sup>3</sup>He-<sup>4</sup>He dilution cryostat has been equipped with a detachable system designed to study specimens placed in strong magnetic field at room temperature;
- we have developed new software for the experimental setup.

### 1. Polarized neutron spectrometer [3]

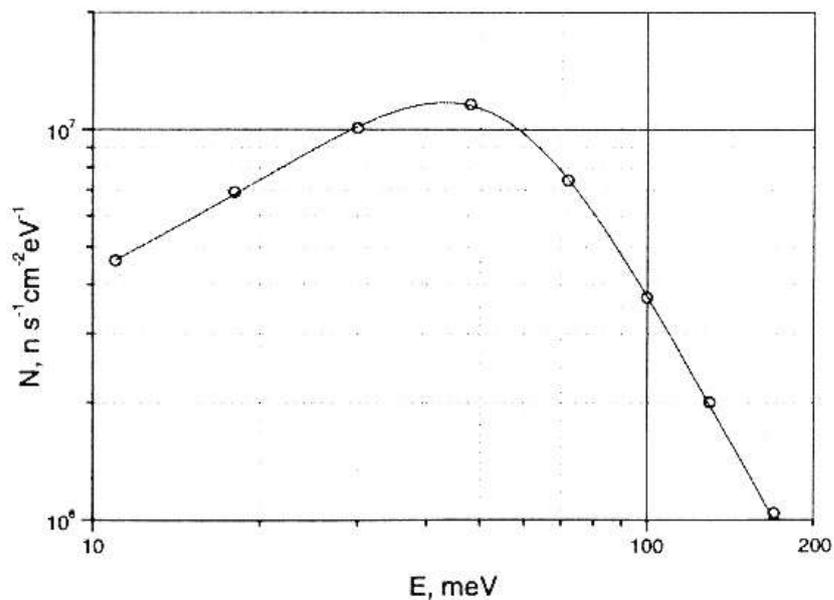
The polarized neutron spectrometer is located on the tangential channel 1 of the IBR-2 pulse reactor of Frank Laboratory of Neutron Physics, JINR. The schematic view of the spectrometer is shown in Figure 1.

We use Co-Fe monocrystals for neutron polarization and polarization analysis. We have measured neutron diffraction for Co-Fe monocrystal in Laue geometry for the range 3–19° of the angle  $\theta$  between neutron beam direction and the surface (200). Table 1 shows the values of  $\theta$  angles used in our measurements and corresponding neutron wavelengths and energies. It also shows the counting speed  $n_l$  and the intensity  $I_l$ , taking into account detector efficiency and the surface of the reflected beam ( $s \cong 4 \text{ sm}^2$ ). As a result of scanning the angle  $\theta$  we determined the maximum of the reflected beam.



**Figure 1.** Schematic view of the spectrometer: 1 – primary collimator; 2 – Sollér collimator; 3 – polarizer crystal; 4 – leading magnetic fields; 5 – Mezei flipper; 6 – shim; 7 – cryostat; 8 – analyzer crystal; 9 — detector.

We used RM-70 ionization chamber, in which the width of  $^{235}\text{U}$  uranium layer is equal to  $100 \text{ mkg/cm}^2$ , for measuring the intensity and spectrum of primary neutron beam hitting the polarizer. As a result we collected data describing the intensity and spectrum of neutron beam in the range of energies from 10 to 200 MeV. In this energy range the intensity of neutron beam was equal to  $1.0 \cdot 10^6 \text{ n/sm}^2\text{s}$ . Figure 2 shows the spectrum of energies measured using the time-of-flight technique.



**Figure 2.** Dependency of the neutron beam density on the energy of neutrons hitting the polarizer.

**Table 1. Parameters of the polarized neutron beam**

Angle $\theta$ , (deg)	19	12	6	4	3
Wavelength $\lambda$ , ( $\text{\AA}$ )	1.15	0.74	0.37	0.25	0.19
Energy $E_n$ , (eV)	0.062	0.15	0.6	1.3	2.3
Counting speed of the detector after the polarizer $n_1$ , (sec <sup>-1</sup> )	800	270	65	33	22
Intensity of the polarized beam $I_1$ , (n/sm <sup>2</sup> sec)	430	200	80	60	50
Counting speed of the detector after analysis $n_2$ , (sec <sup>-1</sup> )	70	23	3.1	0.6	0.2

We have performed several measurements of neutron polarization and obtained polarization values in the range between  $P=0.9$  and  $0.98$  depending on the neutron beam collimation and the strength of the leading magnetic fields between polarizer and analyzer magnets.

### 1.1. Modernization of the polarized neutron spectrometer

As a result of the modernization, we have replaced the outdated operation and control system of the polarized neutron spectrometer [3], which was implemented in KAMAK standard, with a new system which operates via high speed standard USB interface.

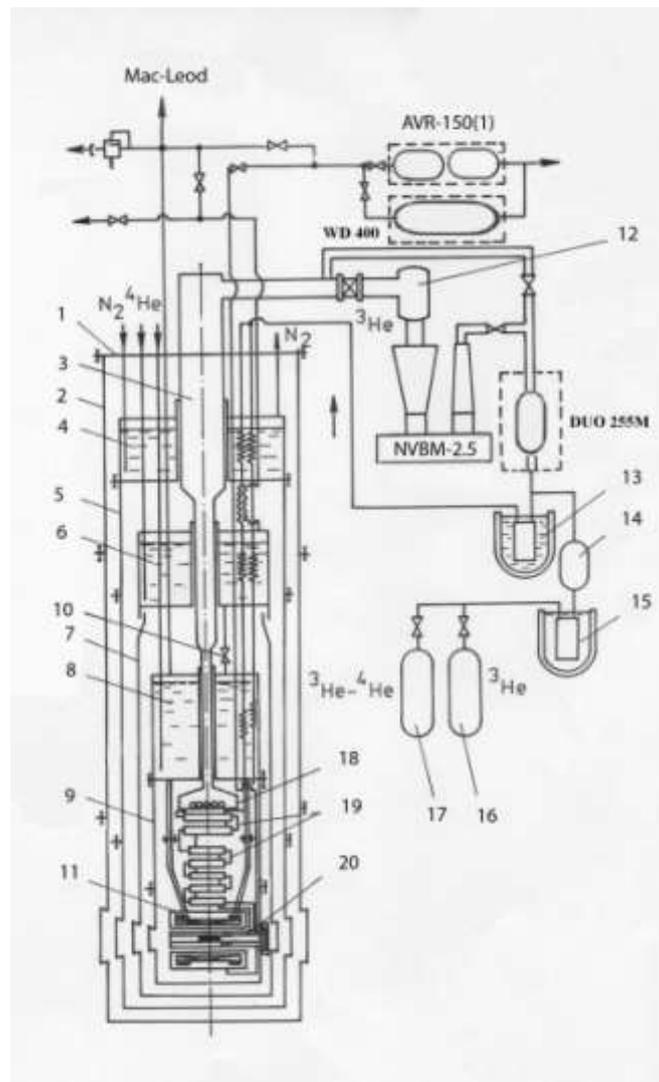
The spectrometer contains four step-engines controlling the movements of the spectrometer and the detector axes, and the rotations of the polarizer and the analyzer. In the spectrometer a system of four 8SMC1-USBh controllers is mounted in a single 8SMC-USBhF-B2-4 rack and is connected with a compute node, which is controlling the experiment. Each of these 4 engine controllers has its own address in the USB line. The selected 8SMC1-USBh step-engine controller is directly integrated with the step-engine driver and has the following characteristics:

- Existence of USB hubs in the units
- Electric current constraint – 1.6 A.
- Existence of constraints on left and right sides (end switches).

## 2. Polarized nuclear target

For polarizing nuclei in KOLKHIDA we use the most generic «brute force» method, which involves cooling of the target in a strong constant magnetic field [4]. For this purpose we have built the <sup>3</sup>He-<sup>4</sup>He dilution cryostat with superconducting solenoids [1, 5] (Fig. 3). We have also foreseen a possibility of dynamic polarization of nuclei. The target is placed into a dilution bath of the <sup>3</sup>He-<sup>4</sup>He refrigerator, in which we achieve  $T=23$  mK temperature at the speed of <sup>3</sup>He circulation  $\dot{n}=1.07 \cdot 10^{-3}$  mole/sec. The dilution bath with the target is located in the center of superconducting solenoid where the maximal magnetic field  $H=5.8$  T and the uniformity of the field in 14 mm a diameter sphere  $\Delta H/H=2.4 \cdot 10^{-4}$ .

## 2.1. Modernization of the $^3\text{He}$ - $^4\text{He}$ refrigerator with superconducting solenoid



**Figure 3.** Schematic view of the  $^3\text{He}$  -  $^4\text{He}$  dilution cryostat with superconducting solenoid: 1 – main flange; 2 – vacuum jacket; 3 – central pipe of the  $^3\text{He}$  pumping line; 4 – nitrogen bath; 5 – nitrogen screen; 6 – helium bath; 7 – helium screen; 8 – pumped helium bath; 9 – helium screen of the dilution step; 10 – cryo-valve; 11 – superconducting solenoid; 12 – nitrogen trap of the NVBM-25 booster pump; 13 – oil filter; 14 – HBF-2 pump; 15 – angular trap; 16 –  $^3\text{He}$  storage reservoir; 17 –  $^3\text{He}$ - $^4\text{He}$  storage reservoir; 18 – vaporization bath; 19 – heat exchanger; 20 – dilution bath.

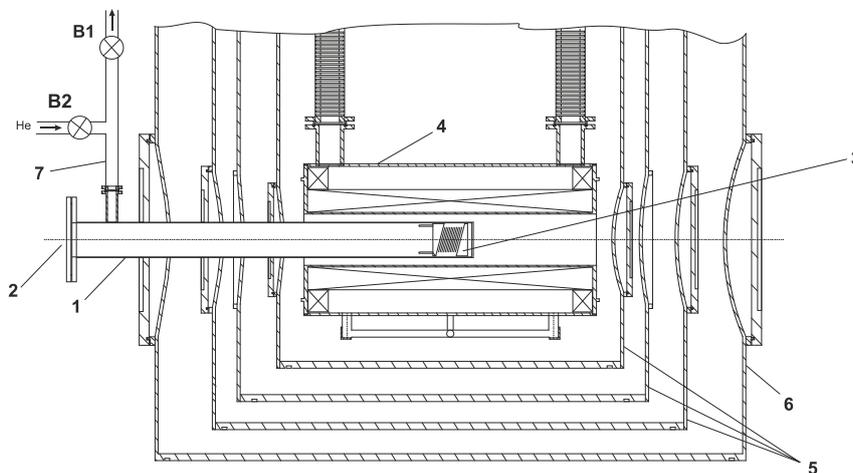
As a result of the modernization:

- We have completely updated the cryostat pump-out system. We have replaced the outdated fore-vacuum and high-vacuum pumps with a set of turbo-molecular pump HiPace 700, DN 160 CF-F, TC 400 with the indication and control unit DCU 400. Fore-vacuum is provided by the two-step plate-rotor pump DUO 20 M.
- On the  $^4\text{He}$  steam flowing line we have replaced one of the ABP-150 units with a CombiLine WD 400 pumping system.
- On the  $^3\text{He}$  circulation line, at the exit of the booster pump HBEM-2.5, we have replaced the ABP-50 vacuum unit with a fore-vacuum plate-rotor pump DUO 255 M.

- Helium level is being controlled by a two-channel LM-510-11 controller with superconducting sensors.
- We have built a “warm sluice” (Fig. 4) for rapid replacement of specimens in strong magnetic field at room temperature.

## 2.2. «Warm sluice»

For neutron studies of specimens in strong magnetic fields at room temperature, we have equipped the dilution cryostat with a detachable «warm sluice» (Fig. 4). The specimen is placed into a vacuum tube 1, which is then hermetically locked by the gag 2. After that the sluice air is pumped out through the B1 valve up to  $10^{-2}$  Top, at the same time keeping the B2 valve closed. In order to avoid covering with frost the sluice 1 and the specimen 3 (because of proximity with helium temperature) before exchanging the specimens we open the B2 valve and, keeping the B1 valve closed, inject helium gas into the sluice. After exchanging the specimens we close the B2 valve and the gag 2, and the system gets pumped out through the B1 valve.



**Figure 4.** Schematic view of the «warm sluice»: 1 – sluice; 2 – gag; 3 – specimen; 4 – superconducting solenoid; 5 – cold screens of the cryostat; 6 – vacuum jacket of the cryostat; 7 – tripple; B1, B2 – vacuum valves.

## 3. Ferromagnetic resonator of neutrons

We have prepared an experiment to study a first category paramagnetic resonance, which occurs when polarized neutrons pass through a polarized nuclear target. It is known, that if inside the polarized nuclear target we create an alternating magnetic field, which is rotating around the polarization direction, then, by analogy with regular paramagnetic resonance, we can observe the transitions between energetic levels of neutrons at  $\omega$  frequency of the rotating magnetic field equal to the frequency of neutron nuclear precession. By placing the polarized nuclear target into a constant magnetic field we can achieve a shift in the resonance frequency, which is caused by algebraic addition of the effective magnetic (pseudomagnetic) field  $H_{eff}$  and the constant magnetic field  $H$ .

In order to carry out such experiment, in addition to polarized neutrons and polarized nuclei, we also need to have a device allowing us to monitor the resonance shift. For this purpose we have chosen the ferromagnetic resonator of neutrons [1, 6]. We have tested a

resonator for 0.062 eV neutrons and currently we are testing resonators for the energy range from 0.15 eV to 2.3 eV.

#### **4. Software system for the KOLKHIDA experimental setup**

Software packages for the KOLKHIDA experimental setup consist of an Experiment Automation System (EAS) and a group of programs for experiment control and operation.

The usage of large amount of specialized equipment, the problems of synchronization of interfaces for this equipment with constantly updating computational hardware, different platform dependencies of system components, as well as a complication of modern experiments lead us to develop EAS as a distributed network system, in which individual compute nodes can play the role of intellectual controllers for a specific equipment.

The method of an experiment is defined by the conditions and methods of the experimental data registration. The existence of large amount of hardware, which defines the conditions for data registration, and the expected new hardware assumes multiple updates in the method of the experiment. This makes the following demands to the way we build software systems for our experimental setup:

- EAS consists of unified, functionally complete executable components, which interact to each other. External interface of a component defines access to procedures, which realize the functionality of given component;
- each component of the EAS is invariant with respect to changes in the experimental method;
- the experimental method is described by unified dialog subsystem. Spectrometer configuration changes do not affect the method description system;
- the components automatically join in EAS according to the experimental task;
- moving software components to other compute nodes within the local network does not destroy the system, does not change the experimental task and does not require recompilation of AES packages;
- an unified control program is managing the execution process for main operations (method) during a running experiment. The algorithm of such control program is invariant with respect to changes in the experimental method;
- the experiment is carried out automatically, with a possibility of switching to a dialog mode;
- the EAS does not require programming skills from its users.

It has been demonstrated [7, 8], that for successful implementation of software components which would satisfy the aforementioned requirements it is critical to solve the following problems:

- development of the experiment control method;
- development of an universal subsystem for the description of experimental method;
- development of specialized tools for searching of the components and their dynamic coupling.

During the software development process the EAS components have been classified according to their functional purpose and the way they interact with other components in the

system. We have used our experience acquired by developing distributed network applications. Besides the software system designed to solve main experimental tasks, we have developed the programs for tuning the experimental setup, preliminary data analysis, data visualization, visualization and monitoring of the experimental setup conditions and many others. In this paper we restrict ourselves in describing the tools which ensure the following characteristics of the KOLKHIDA setup: reliability, flexibility, reduced modification time of the EAS software by having a possibility to reuse existing software components in various experiments, the possibility for users to adjust EAS to a new experiment without requiring programming skills. As a result these features increased the effectiveness of researchers' work.

#### **4.1. Experiment Control System**

For automated controlling of the experiment it is necessary to have (and is always available) some description of the experimental method. A traditional way of doing this is to describe the experimental method by listing procedure calls. Such a list is either implemented in the programming language of the Experiment Control System (ECS), or is provided to the system as a script, which is parsed by an interpreter included in the ECS. As a result we have fixed interdependency of the components, which makes the unification of the ECS difficult. It has been suggested [9] to drop the experimental method description tools from the ECS and to use an alternative approach to the experiment control procedure as follows:

- the experiment control system has a frame structure [10] and it sequentially executes two processes — building of experimental conditions and data registration under these conditions;
- concrete implementation of these two processes is selected dynamically at run time by using a special configuration file which contain data registration conditions and which is created by the experimental method description subsystem.

#### **4.2. Experimental method description subsystem**

The experimental method description subsystem [11] includes one database and two dialog programs. One of these dialog programs is used by the programmers for creation of passports for the components interacting with data registration condition control devices. The second dialog program is used by the researchers for building PSJ (Preparation of Single Job) tasks.

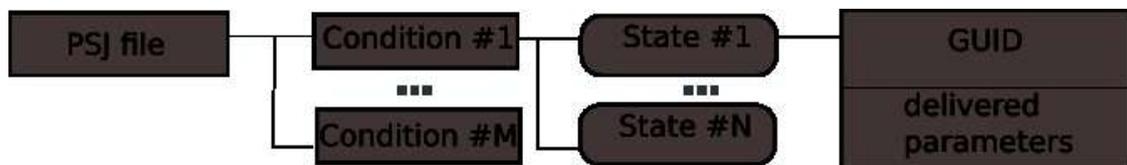
**4.2.1. The device passport creation program** creates JSON descriptions of devices and stores them into the database. Each description includes: the name of the controller and the list of devices connected to this controller, the type of the component which interacts with the controller, its GUID which is used for referencing the component, and the description of parameters. The list of parameters (applied protocol) is defined by the component software developer.

**4.2.2. The PSJ task building program** uses the list of available devices (and components) retrieved from the database. Using the program GUI the researcher selects required components and builds a list of devices, which will determine the conditions of data registration during the experiment. For each of these devices it is possible to define a list of consecutive values for the controlled parameter. As a result of this operation we get a PSJ-file

with a tabular description of final automated device, which implements stages of the operational system required by the experiment. The data is being exposed at each of these stages. Figure 5 shows the structure of a PSJ file.

The difference between this method and the methods implemented by other systems is that the PSJ task building program creates a list of data registration conditions instead of describing the operations as a list of procedure calls in a script or hardwiring the procedure implementation in the code. The experiment control system manages the components used in given configuration, while the tasks of selecting and executing procedures implementing the required conditions of data registration are delegated to device control components, which do that based on the interpretation of the condition descriptions.

The advantage of given approach is that for describing the experimental method a researcher needs to deal only with the problematic region: names of spectrometer components, angular positions etc. The GUID and the type, which are used for searching the components to which the configuration parameters need to be delivered, are automatically transferred from the device passport into the PSJ file.



**Figure 5.** Structure of a PSJ file.

### 4.3. DiCME (Distributed Component Messaging Environment)

#### 4.3.1. Requirements for DiCME

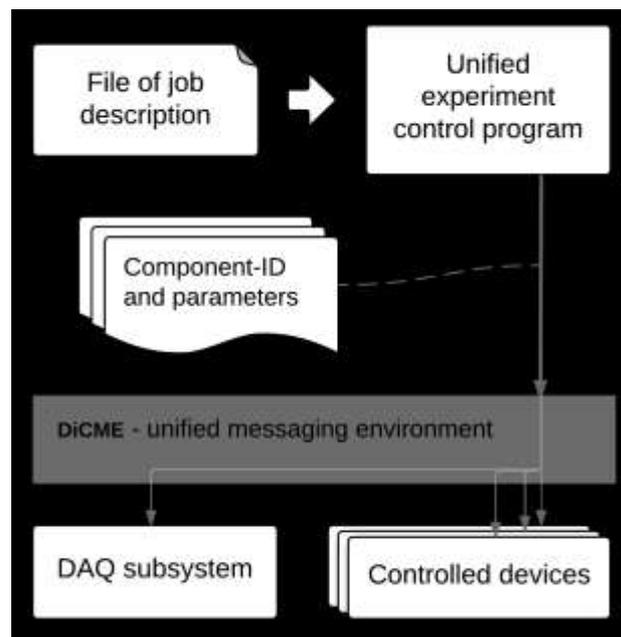
The Distributed Component Messaging Environment [12] has been developed to satisfy the following requirements:

- automated searching and binding of the components;
- leverage the asynchronous mechanism of remote procedure calls, because by calling remote procedures synchronously we are increasing the communication time between EAS software components, and this has a negative effect on the system throughput;
- allow passing a message to several components simultaneously;
- the same DiCME tools need to analyze all messages within EAS, because the homogeneous systems are much easier to develop and support;
- transparency of communications within the distributed system: each component should be able to communicate with any other component in the system by using the same mechanism independently of the location of components inside the network (either the same or another compute node, possibly also of a different type);
- possibility to move components between compute nodes within the system, which should facilitate fixing the problems related to compute node failures;
- component failure, node failure or disconnected network should not bring the entire system down;
- the system should be able to automatically adapt to the given configuration.

**4.3.2. Dynamic binding of the components.** One of the important features of DiCME is a mechanism for component binding. Information for late (dynamic) binding is read from the PSJ file. The PSJ task building program automatically writes to the file the component's identifier and type, which are defined in the passport. Such mechanism works more efficiently compared to other similar mechanisms traditionally used in building software components for experiment control systems.

The procedure of passing messages over to the executable component (SendMSG) has been defined and fixed.

Figure 6 shows a schematic view of the communication between the experiment control system and DiCME components during execution of main EAS tasks.



**Figure 6.** Schematic view of the communication between the experiment control system and a DiCME component during execution of main EAS tasks.

The experiment control system uses a PSJ file as an input. The program selects a description for the next state of the system (list of data registration conditions) and passes descriptions of each condition to the DiCME component. Each condition description contains a list of parameters as well as some information about the component (e.g. GUID, type), which is sufficient for locating the component and binding it to the experiment control program. DiCME locates the required component and sends them a condition description message, which contains a list of parameters. The list of parameters gets interpreted by the component procedures. For example, for controlling the polarizer position the corresponding JSON condition description looks as follows:

```
{device:"polarizer", parameter:"angle", value:"30 grad"}
```

Each component, which received a message from the experiment control system, must reply with an operation completion signal («Done»/«Error»). After collecting signals from all devices listed in the description of given EAS condition, the experiment control system

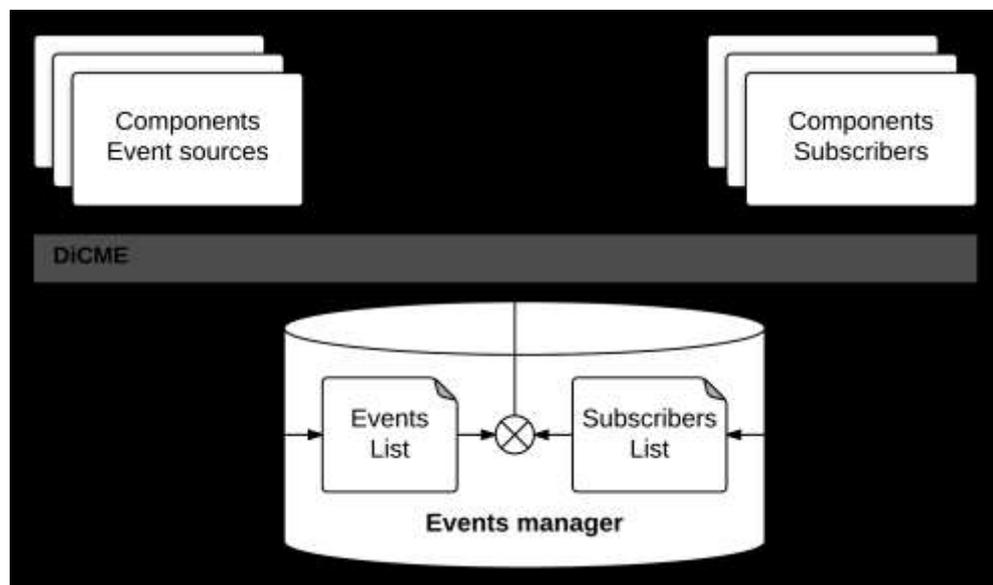
enables data registration by the DAQ subsystem. Data exposition completion signal allows the control system to start analyzing next condition in the PSJ file.

In the dynamic binding mechanism all information required for component binding and parameterization of actions is produced by the tools which are external with respect to the control system, components and DiCME tools. Unlike CORBA and other similar technologies, the dynamic binding mechanism eliminated the need in preparatory communication between components for configuration of remote procedure execution. Thanks to the automated building of component registry in DiCME, the binding algorithm executes at the same speed as the static binding. The binding algorithm does not prevent the evolution of the experimental method. Modifications within the experimental method do not affect the control system and a DiCME component because both the control system and DiCME are transparent for the list of parameters.

**4.3.3. Execution of auxiliary functions.** The following features have the most significant effect on the execution mechanism of auxiliary functions:

- spontaneous appearance of information about the events and a possibility of delayed analysis of this information;
- the need to pass information to several processes. The sender of this information is not always aware of the list of recipients. One may vary such list at runtime on user's request.

For binding of the auxiliary components we have chosen a variation of the «subscription» algorithm. In this algorithm consumer components subscribe to information of given type, and once such information becomes available a special component (message manager) delivers it to all subscribed consumer components. Figure 7 shows schematic view of the message manager, which uses a DiCME component for serving auxiliary operations.



**Figure 7.** Schematic view of the message manager, which uses a DiCME component for serving auxiliary operations.

As a result, the implementation of auxiliary operations via DiCME together with a mechanism of automated location of components allows the researchers to dynamically build the system with required auxiliary functions by simply launching the required component on any compute node within local network.

## Conclusion

As a result of the modernization of the KOLKHIDA experimental setup we have upgraded the polarized neutron spectrometer control and monitoring system. We have completely updated fore-vacuum and high-vacuum pumps of the  $^3\text{He}$ - $^4\text{He}$  dilution cryostat. The cryostat has been equipped with a detachable system designed to study specimens placed in strong magnetic field at room temperature. We have developed new software for the KOLKHIDA setup.

The described technology of building EAS software packages ensured a high degree of software inheritance and allowed us to minimize software modification time. The users can configure the system with new set of parameters in ~10 min. The EAS does not require programming skills from its users. The runtime performance measurements demonstrated that the usage of the unified mechanism of cross-component interactions over the network, instead of direct function calls, does not have a negative effect on overall system performance.

## References

1. *Abov Yu.G., Alfimenkov V.P., Lason L., Mareev Yu.D., Pikelner L.B., Tsulaia V.M., Tsulaia M.I., Salamatin I.M.* // Kolokhida Instrument for Experimental Investigations of Interactions of Polarized Neutrons with Polarized Nuclei, Nuclear Instruments and Methods in Physics Research, A, v. **601**, i.3, 4, 2009, p. 317–325.
2. *Baryshevsky V.G., Podgoretsky M.I.* // Nuclear precession of neutrons, ЖЭТФ **47**, 3, 1050 (1964).
3. *Abov Yu.G., Alfimenkov V.P., Galinsky E.M., Lason L., Mareev Yu.D., Novitsky V.V., Pikelner L.B., Tsulaia V.M., Tsulaia M.I., Chernikov A.N.* // Polarized neutron spectrometer, ПТЭ, **3**, 2000 p. 9–12.
4. *Khutsishvili G.R.* // Oriented nuclei, УФН **53**, 1954, 381–412.
5. *Tsulaia M.I., Tsulaia V.M., Alfimenkov V.P.* //  $^3\text{He}$ - $^4\text{He}$  Dilution Cryostat for Investigation of Interactions of Neutrons with Polarized Nuclei Bul. Georg. Nat. Acad. Scien., v. **2**, 4, 2009.
6. *Chelmicki L., Dobrzynski L., Tsulaia M.I.* // Theory of Neutrons Resonators, Nucleonika, 1980, **25**, 6/80, p. 879.
7. *Salamatin I.M., Salamatin K.M.* // Applied Informatics, 2014. № 5(53), с. 60–80.
8. *Саламатин К.М.* // JINR P13-2013-72. Dubna, 2013.
9. *Ignatovich V.K., Salamatin I.M., Salamatin K.M., Senner A.E.* // Information technologies, 2014. №12, с. 63–68.
10. *Gorbunov-Posadov M.M.* Distensible programs // М.: Полиптих, 1999. 336 с.
11. *Salamatin K.M.* // JINR P13-2013-92. Dubna, 2013.
12. *Salamatin K.M.* // Software Engineering, 2014. №3, p. 3–11.
13. *Gundorin N.A., Dikumar N.D., Mazny N.G. et al.* // Известия РАН, серия Физическая, 2009, том **73**, №2, с. 261–263.