Automated data acquisition and processing system as a key unit of a biharmonic laser spectrometer

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Received July 29, 2002

The basic design, composition, and structure of an automated data acquisition and processing system (ADAPS) for a biharmonic laser spectrometer are considered. The system operates in real time and provides acquisition, storage, and preliminary processing of the data obtained from the spectrometer instruments and units, as well as interactive (on operator commands) or automated (on control program commands) control over separate spectrometer units. The system accepts those measurements, which most closely correspond to the goal to be achieved, and rejects the improper ones. Functional diagram of ADAPS is presented. Interrelations are considered between its constituent parts, units, and modules; working algorithm and interface are described.

1. Statement of the problem

Recording molecular re-emission spectra with a diffraction spectrograph equipped with a CCD array has no difficulties when traditional schemes of medium excitation by a laser beam are applied.[1] The problems mainly arise when molecules are excited by a biharmonic laser radiation (at ω_1 and ω_2 frequencies) and medium re-emission process depends not only on the intensity (I_1 and I_2), duration ($\tau_1 \approx \tau_2 \approx \tau$), and polarization of biharmonic laser radiation pulses, but also on their frequency difference ($\Delta\omega = \omega_1 - \omega_2$) and sum ($2\omega_s = \omega_1 + \omega_2$), time ($\delta\tau$) and spatial ($\delta L$) interval between the pulses.

It is exactly this set of parameters of exciting biharmonic radiation that is needed for experimental verification of hypothesis for generation of a field having large angular momentum (AM) in a molecular medium.[2,3]

The main part of a laser spectrometer providing verification of such a hypothesis is a biharmonic laser system (BLS). BLS consists of two Nd:YAG lasers coupled by means of electrooptical cross feedback.[4] A great drawback of such a BLS is a strict requirement (at the level better that 1%) to stability of the pump level in both channels.[5] This dependence is fundamental, it could not be eliminated that result in large fluctuations of the pulse intensity of both laser radiation components and time delay $\delta\tau$ between them.

It is obvious that the above-mentioned fluctuations will superpose on the interaction between exciting radiation and molecules that will lead to two negative results. *First*, excitation dynamics of every molecule with biharmonic radiation will be changed and, correspondingly, probability of redistribution of interaction energy between intramolecular channels will be also changed. *Second*, the necessity will arise of separating out the desired signal against the background of random noise caused by medium re-emission due to fluctuation of exciting laser pulses mentioned above. All this will make doubtful the results of verification of the hypothesis on generation a field having large angular momentum in a molecular medium.

Thus, it is urgently needed to supplement a biharmonic laser spectrometer with an automated data acquisition and processing system (ADAPS) that eliminates both of the negative results.

2. Requirement imposed on ADAPS

An automated data acquisition and processing system (ADAPS) should satisfy the following requirements:

(1) To exert control over operation of separate units, instruments, and modules of the spectrometer by commands from an operator or in an automated mode.

(2) To follow the parameters of every laser pulse (including radiation frequency, time, $\delta\tau$, and spatial, δL, delay between pulses, and relation I_1/I_2 between intensities of biharmonic components) in the course of accumulation of the measurement results in a data buffer on the time interval ΔT.

(3) To store the data obtained in structured files (database) that allow fast search of information in the data array stored.

(4) To delete improper data from the array.

(5) To provide:

– acquisition, continuous monitoring, and indication of data in the form that would allow an operator to optimize experimental conditions;

– simplicity of changing an arrangement of units, instruments, and modules of the spectrometer including incorporation of new ones;

– possibility of fine adjustment and modification without re-compilation of the main ADAPS software modules in accordance with the investigations performed;

– fast access to various data both buffer and processed ones.

0235-6880/02/11 920-06 $02.00

3. Composition and functions of ADAPS hardware

The ADAPS hardware includes the following instruments, units, and modules (Fig. 1).

(1) *Unit of Frequency (Wavelength) Tuning* of BLS radiation that operates in the following way. A computer-controlled stepper-motor drive changes an inclination of a Fabry–Perot etalon placed in one of the BLS channels and allows one to scan and tune laser radiation frequency (wavelength).

Scanning and frequency (wavelength) tuning of laser radiation is provided by a stepper motor module that is operated by a command from a computer.

(2) *ILD-2M Pulsed Energy Meters.*

The heads of two ILD-2M meters allow one to measure a ratio (I_1/I_2) between intensities of laser radiation components (ω_1 and ω_2). The information on laser pulse energy is entered into a PC by means of CAMAC-modules of analog-to-digital converters (ADCs). Supplementary voltage followers, placed between ILD-2M meters and ADC modules, reduce electrical noise induced. Both meters operate permanently and independent of a control computer.

(3) The *IDV-3 Two-Channel Wavelength Meter* is a coupled unit of Fizeau interferometers from which the radiation comes to FUK-1L1 photodiode arrays.

The heads of the IDV-3 wavelength meter are connected to the computer by means of a modified CAMAC-module of the ADC and specialized control circuit that provides functioning of the photodiode arrays. Initiation of the photodiode array is fulfilled immediately before the laser pulse by a command from the control computer. Time delay is determined by module of general synchronization.

(4) *DFS-452 Diffraction Spectrograph* and ILX-511 CCD array placed into a cassette holder of the spectrograph provide for recording the re-emission spectra of the media under study. The CCD array is connected to the computer by means of specialized control circuit and modified CAMAC-module of the ADC.

Initiation of the CCD array is fulfilled immediately before the laser pulse by a command from the control computer. Time delay is determined by the module of general synchronization.

In the case when the CCD array operates in a "storage" mode, the erase cycles are switched off but the initiation moment is synchronized with the laser emitter as before.

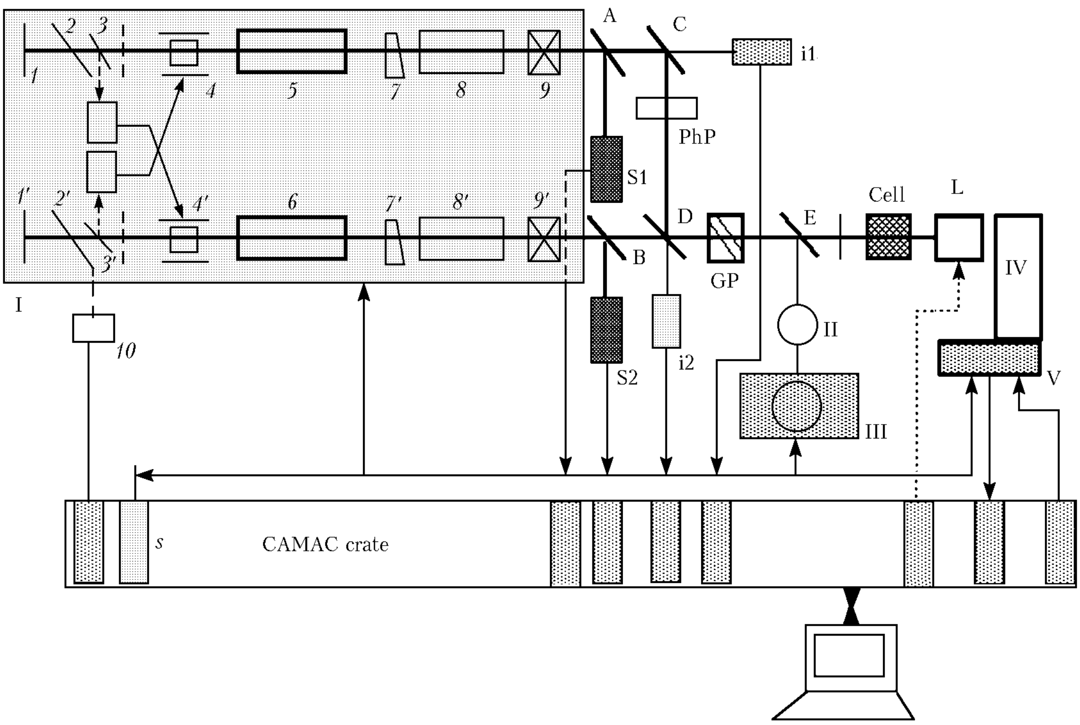

Fig. 1. Block diagram of the experimental setup: totally reflecting mirrors *1* and *1′*; Fabry-Perot etalons *2* and *2′*; polarization mirrors *3* and *3′*; electrooptical shutters and control units *4* and *4′*; active elements of master oscillator *5* and *6*; output windows *7* and *7′*; active elements of amplifiers *8* and *8′*; frequency doublers *9* and *9′*; a stepper motor and mobile parts *10*; wavelength meter heads i1 and i2; ILD-2M meter heads S1 and S2; the general synchronization module *s*; 10-% (at 530 nm) reflection mirrors A and B; 100-% (at 530 nm) reflection mirror C; 50-% (at 530 nm) reflection mirror D; 100-% (at 1060 nm) reflection mirror E; a controllable phase plate PhP; a Glan prism GP; Cell; a tunable interferometer – rejection filter L; the laser I; a FEK-19 PMT II; a C7-19 oscilloscope III; a DFS-452 spectrograph IV; an ILX-511 unit V.

(5) *Electrically Tunable Fabry–Perot Interferometer* is installed in front of the DFS-452 spectrograph and operates as a comb filter suppressing illumination of ILX-511 CCD array by exciting biharmonic radiation.

The interferometer is tuned synchronously with the laser radiation frequency tuning by means of a programmable voltage source, which is controlled by digital code from CAMAC. The voltage source is based on a pair of high-voltage n-channel MOS transistors controlled by high-quality operational amplifier. The gain of the latter is preset by a digital code. The voltage source provides a d.c. voltage from 0 to 150 V with the step of 30 mV at piezoelectric plates of the interferometer.

(6) *Synchronization module and CAMAC hardware.*

Instruments, units, and modules of ADAPS are connected to a computer by means of a crate system (CAMAC) that gives the largest freedom at the stage of searching optimal experimental conditions.

The module of the general synchronization provides a proper order for initiation and scan of the instruments, units, and modules of ADAPS. Synchronization is realized by means of timers from the CAMAC-modules. Every operating cycle of these timers starts to operate by a command from the control computer. The timers prescribe time interval between the laser initiation and initiation of ADCs and photodetector arrays.

The CCD array operation modes, including “storage” one, are prescribed by complementary control signals that come from CAMAC registers and enter into the control unit of the CCD array.

In creating ADAPS based on CAMAC, low channel carrying capacity was a certain difficulty. This difficulty has been overcome by means of modification of some CAMAC-modules. Thus, ADAPS is coupled with photodetector array by means of a storage ADC, whose memory volume/scan cycle has been brought into one-to-one correspondence with the array volume; some extra data (for example, the Fizeau interferometer temperature) have been entered into the ADC free memory cells but not into separate CAMAC modules. Besides, CAMAC-modules have been grouped in such a way that makes the best use of the signals automatically generated by the modules and avoids unnecessary refers to them for the status scan.

4. ADAPS software

The standard software for laboratory measurements' automation (like LabVIEW and similar software) would not do for realization of ADAPS because they do not provide the rate of data processing required for the spectrometer operation.

Furthermore, requirements imposed on the ADAPS and its software (see Section 2) makes it impossible using an ordinary approach to the development of data acquisition system in which the external devices are scanned in series during some measurement cycle.

To make our software, we used “multithread model” (Ref. 6). In this case the main measuring cycles, characteristic of every type of ADAPS external devices, are performed as subroutines (threads) executed “in parallel.” Priority of executing these subroutines is determined, based on function and character of the specific device, in such a way that an optimal share of the processor time among the threads and processes in the ADAPS be automatically set due to competition between threads.[6]

The software is made on the base of OS/2 *general-duty* operating system, in which the context switching time does not exceed 50 μs. Time interval, during which the cycle of data acquisition and preliminary processing as well as the cycle of interaction with a user should be completed, is determined by the laser pulse repetition rate and it equals to 80 ms. At call to the external devices (CAMAC), execution of processes and threads not connected with this call is almost completely blocked for ~ 40 ms. The rest of measuring cycle (approximately 40 ms) is enough for execution of hundreds of thousands of computer commands when up-to-date PC is available (on the basis of AMD Duron 600 MHz processor). This circumstance and choice of an operating system with minimum context switching time allow us to divide the software into separate functional modules that are executed on different time scales.

Let us consider the functional diagram of the software modules (Fig. 2) and their interaction.

Interaction with the instruments, dialog with a user, and data processing are executed by *independent* software components. Interaction between the software, CAMAC, and the spectrometer units is realized by means of CamCtl program. The IDVserver program works with the heads of wavelength meter. The Archivarius program stores preliminary data in temporary files on a hard disk and then puts them into the database. The user's interface makes it possible to control the system operation and to observe the data acquired and processed. Owing to separating functions between program components of the software, the only module acquiring data and controlling the spectrometer (CamCtl) operates in real time (critical time is approximately 1 ms). Other programs, except some threads storing data, executed under standard priority and do not interfere high-priority process of data acquisition and spectrometer control.

To manipulate with large data arrays, the software uses mechanism of shared memory that gives minimum burdens. Storage of the data arrays in the above-mentioned shared memory gives a possibility of easily combining the programs and modules of the software.

Using all the possibilities of the instruments, units, and modules of the ADAPS requires a sufficient computational work. Thus, for the CCD array that records the re-emission spectra it is necessary to take into account a dark current and non-uniform sensitivity over CCD cells. To record weak signals, one needs to smooth signal and suppress noise, moreover different data reduction algorithms should be applied for different measurements, some of these algorithms perform such cumbersome procedures as discrete Fourier transform.

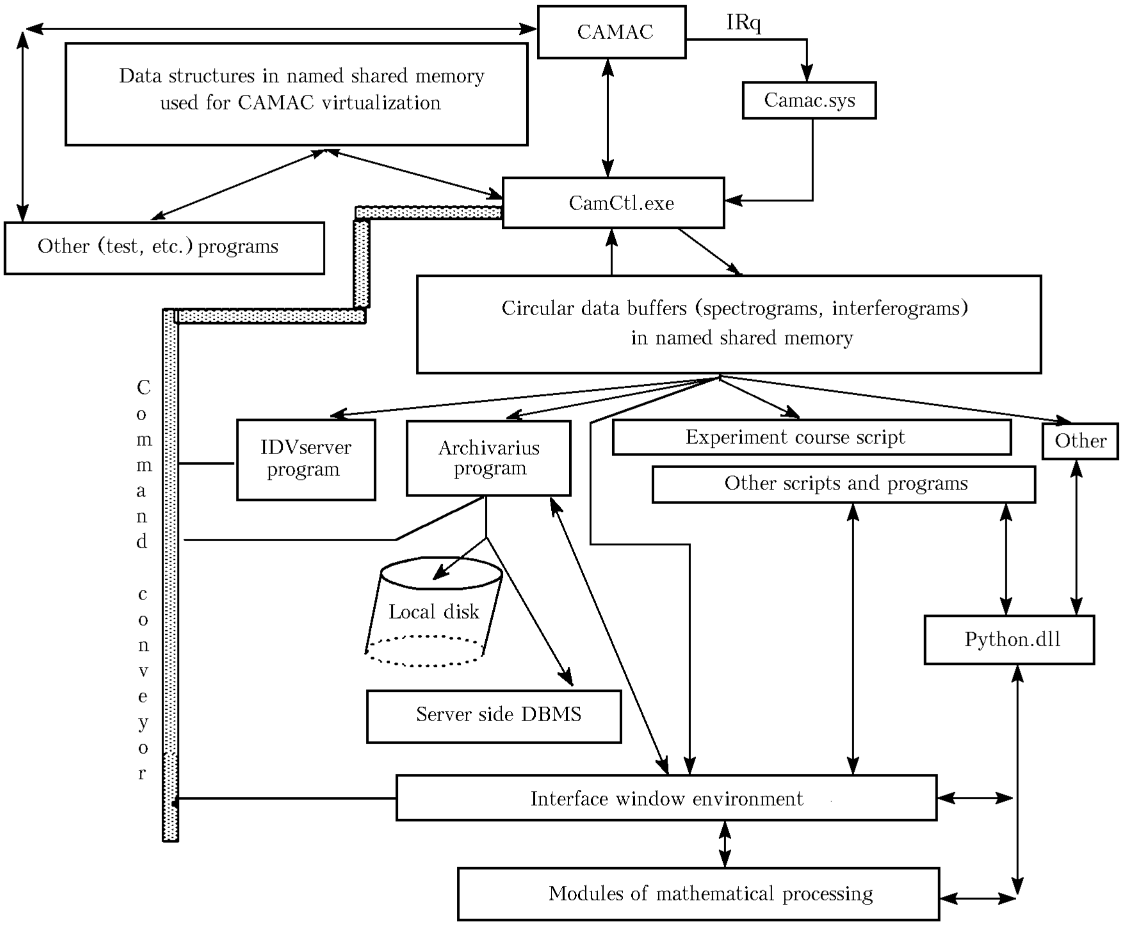

Fig. 2. Software structure.

The requirements imposed on the ADAPS and its software (see Section 2) provide continuous monitoring of spectrometric data needed for an experiment optimization, therefore a part of cumbersome computational work is carried out in parallel with the data acquisition and control over instruments, units, and modules.

To ensure that computational procedures do not result in failure in data acquisition and instruments' control processes, the data acquired from the instruments are separated into two flows – preliminary processed and raw data. Both of these flows are stored in a circular buffers that are also located in the nonswapable shareable area of the memory. In the course of an information processing only data from the buffer are used that do not influence time-dependent parts of the software.

The circular buffer volume is chosen in such a way that, on the one hand, not to lose the data and, on the other hand, not to bring extra burdens for memory spooling. The particular memory volume marked as a circular buffer depends on the random-access memory available, as well as on the number and type of the processes to be executed simultaneously. It is determined experimentally. In most cases 8 Mbytes of shareable memory was sufficient for buffer on the computer having random-access memory of 128 Mbytes.

The above-described separation of the ADAPS software into time-dependent parts operating directly with the instruments and the user's code (it is probably slow operating) processing the data made it possible flexible operation with the spectrometer instruments, namely, when incorporating an additional device or changing an operation algorithm there is no need to rearrange all the software code. Simplicity of modifying the time-dependent parts of the software operating with the instruments is achieved due to application of the object oriented approach. In this case the subroutines operating directly with CAMAC modules are made on C++ language in such a way that every class of modules has its own inheritance hierarchy resulting from the common parent, i.e., from CAMAC-module abstraction. The basic parent contains a code that facilitates combination of modules and processing the errors. Such an approach allowed us to easily supplement additional devices, units, and modules and, correspondingly, new codes into the current software.

Owing to Python super high-level computer language interpreter embedded into the software, the ADAPS can be easily tuned to different types and modes of operation. (CPython 2.2.1c.2 interpreter version compiled by VAC 3.6.5 compiler routine has been used. For a more smooth interpreter operation in combination with other ADAPS modules, its main cycle has been modified so that excessively aggressive capture of time quanta intended for the interpreter has been excluded.)

Application of the embedded interpreter routine made the programming process much more simpler and allowed us to use simple scripts to control the spectrometer, to escape from multiple software reworking (inevitable in traditional data acquisition software) when changing the spectrometer configuration or performing out-of-order operations. From the script one can both to control functioning of the spectrometer instruments and to make mathematical data processing.

The spectrometer operation is controlled from the graph interface routine (Fig. 3). When starting the control program, the *profile.py* standard script is executed that contains special code binding the spectrometer instruments and its software with *Python* objects. As a result, the spectrometer instruments and buffer data become available for all user programs and scripts. The data of the spectrometer instruments are presented as matrix objects of the *Numeric Python* module with which one can carry out any operations including discrete Fourier transform. If a necessity arises to change the data processing algorithm or the course of the spectrometer operation, it will be enough to correct “profile.py” script or to write corresponding lines in the script’s editing window.

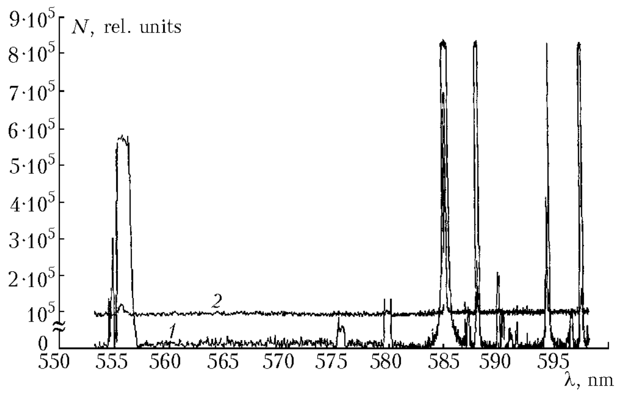

Fig. 3. Spectrum of TN-0.2 Ne lamp at the wavelength of 585 nm. Plots are shifted relative to each other; exposition time 80 (curve *1*) and 1.6 ms (curve *2*).

5. Results of ADAPS operation approbation

The ADAPS and the software described provide long-term data acquisition from the spectrometer (storage time is limited only by the disk memory volume, moreover, the data can be transferred trough a net into a file server). Preliminary data processing is carried out in parallel with the data acquisition and manipulation of the spectrometer. Parameters of the ADAPS and its software are presented below.

Type of interface	CAMAC
Duration of measurement cycle, ms	≥ 80
Recording of a spectrogram	ILX-511 CCD array with 2048 elements
Mode of spectrogram record	continuous, pulsed
Exposure time for spectrogram, ms	from 1.6 to 800
Storage mode	electric + + arithmetic
Resolution, Å	≤ 0.1
Record of interferogram	2 × FUK-1L1 photodetectors array with 1024 elements
Mode of interferogram record	continuous, pulsed
Exposure time for interferogram, ms	from 1.6 to 3200
Control of spectrometer operation	manual or according to script
Observation time	limited by disk memory volume
Required disk memory volume without compression, kbytes/s	100.5
Compression factor	from 1 to 16 times (using ZLIB library)

One more feature of the ADAPS designed is a feasibility of its easy modification for integration with the Internet and operation in a “distant mode,” for instance, for remotely performing “experiments” in training.

Figure 4 illustrates application of ADAPS for recording a fraction of TN-0.2 neon lamp spectrum used for calibration of the spectrometer frequency scale. The software has made on-line subtraction of the dark noise of the CCD array, correction for the nonuniformity of its amplitude-frequency characteristics, and smoothing the noise by moving average over 7 points. Advanced algorithms[7] for data reduction and noise smoothing can also be applied.

To take into account the nonuniformity of a CCD array amplitude-frequency characteristics in the range of 530 nm, the software uses a table of correction factors obtained by means of measuring illumination at the chosen wavelengths when known attenuation has been put in the recording channel. The attenuation required was obtained by turning thin glass plate with known refraction index in the polarized light beam (near Brewster angle). The differences between calculated and measured attenuation were put in the table.

Seeking of peculiarities in the re-emission spectra is carried out by applying discrete Fourier transform to the files containing preliminary processed spectrograms and consequent analysis of the obtained set of coefficients. Data containing peculiarities overwrite from temporary files to structured database files. Local database is made on the basis of *Berkeley DB* library.

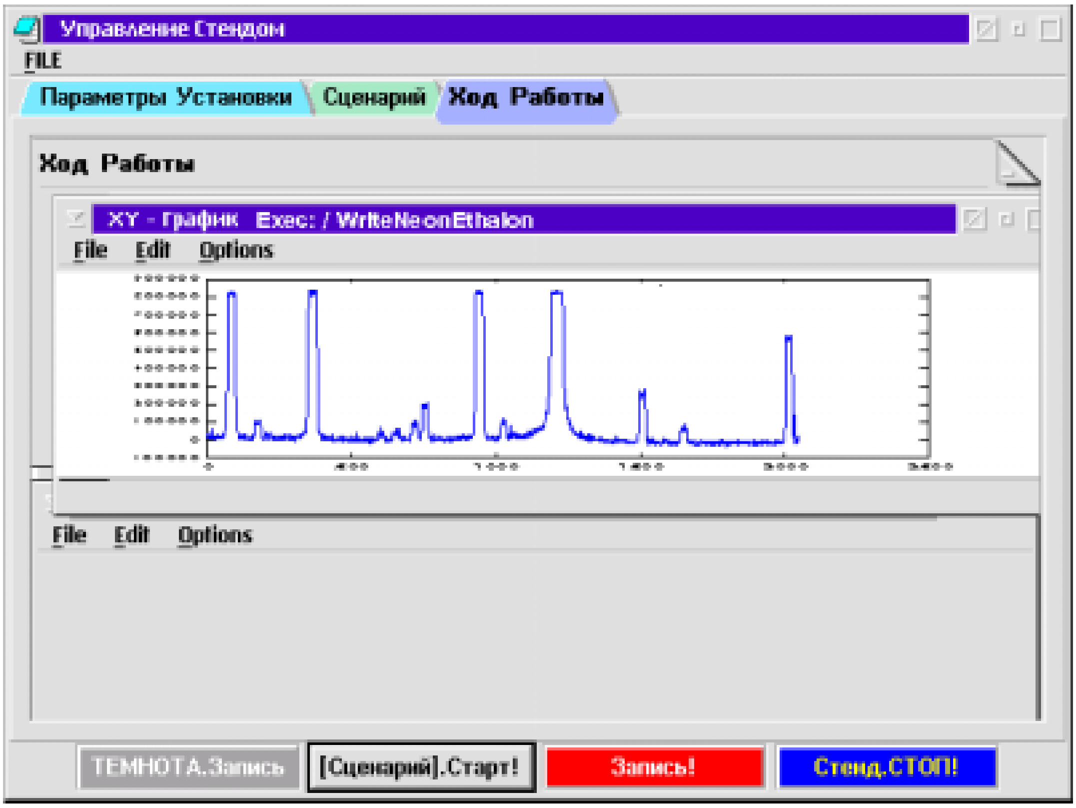

Fig. 4.

Acknowledgments

The authors are thankful to Dr. M.M. Makogon for valuable discussions and to Dr. A.N. Kuryak for his help in making control units for the photodetector arrays and for modification of the CAMAC modules.

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