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Data acquisition and control system for an evolving nuclear microprobe

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ABSTRACT

The application possibilities of the nuclear microprobe are constantly evolving which places new requirements on the data acquisition and microbeam control systems. MeV SIMS experiments for example, require the ability to pulse a continuous beam and steer it in the X-Y plane. For channeling RBS and STIM experiments, the sample needs to be rotated over two axes. Once it is positioned in the channeling direction, patterned irradiation may be needed. Additionally, with the evolution of digital electronics, it is now possible and sometimes preferred to perform signal processing in the digital domain as oppose to analogue signal chains in NIM modules.

In this work we present the most recent upgrades to the data acquisition and control system developed at Rudjer Boskovic Institute. A data acquisition/control system based on a Xilinx Virtex 6 FPGA was developed which can evolve with the microprobe and be reconfigured for various applications. The real time reprogrammable nature of the FPGA coupled with a modular design approach, allow for the ADCs, processing algorithms and communication protocols to be interchanged and upgraded while keeping a constant user interface through the SPECTOR software package.

1. Introduction

The modern nuclear microprobe is a very flexible platform on which a wide variety of experiments can be performed. To maintain this degree of flexibility, the data acquisition and control system has to be able to interconnect and synchronize the many different subsystems that make up a nuclear microprobe. Not every experiment performed on the microprobe is the same and therefore beam modification requirements, sample positioning and even the type of data acquisition varies. The standard solution is to use nuclear instrumentation modules (NIM) and manually connect only the modules that are required for the experiment.

NIMs are the foundation of the nuclear data acquisition and control industry because they provide a flexible, reconfigurable, easy to use platform which can be adapted and used for a wide variety of experiments. However experiments today have become very complex and require precise control of many parameters. This in turn requires many interconnected modules, which limits the performance, increases complexity and introduces noise. Digital Field Programmable Gate Array (FPGA) technology has evolved significantly and can be used in conjunction with NIM for modern experiments. FPGA technology has been readily used for DAQ systems and many commercial solutions exist as described by Bettiol et al. [1]. However no ideal solution exists and there is always a balance between the complexity of the DAQ system and its usability.

This paper builds upon the work of M. Bogovac et al. [2] by adapting more of a modular design philosophy and removing limitation of a closed system. The reprogrammable nature of FPGAs make it a versatile tool for a wide variety of applications and to fully take advantage of this, the hardware and software surrounding the FPGA has to be designed with this in mind.

The implementation of this design philosophy to the upgrade of the data acquisition and control system for the nuclear microprobe and developments to the SPECTOR software package [3] are presented.

2. Data acquisition and control system

2.1. Overview

The new data acquisition system is based on the Xilinx Virtex 6 ML605 development platform consisting of 1 GB of onboard DDR3 RAM, Ethernet connectivity and two FPGA Mezzanine Card (FMC) connectors as described in [4].

The Ethernet connectivity allows the system to be independent of a specific computer, allowing any computer running the SPECTOR software package to communicate with the board. While the two FMC

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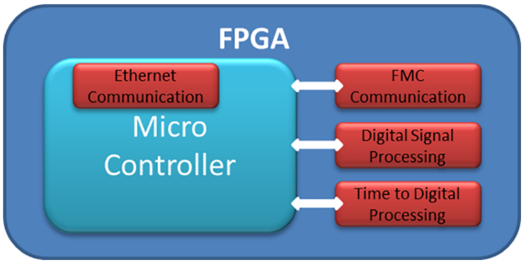


Fig. 1. FPGA Design.

connectors allow experiment specific modules to be added or removed as required. For most experiments a 8 channel 14 bit 250 MSPS ADC card from 4DSP (FMC108) [5] is used along with a custom made FMC card. Using these two FMC modules, detector signal acquisition is possible straight from the pre amplifier or through a NIM analog signal chain and a NIM ADC.

2.2. FPGA

The FPGA code consists of a main communication and control module that runs on a Microblaze microprocessor and interchangeable processing modules, which are independent of the microprocessor as illustrated in Fig. 1. The processing modules were designed using the MathWorks Simulink [6] software package and transcoded into VHDL using Xilinx System Generator [7] allowing for algorithm verification through simulation.

The microprocessor allows for asynchronous communication over a standard TCP protocol giving the system a server role and making it independent of a computer. While the time critical aspects are implemented in the FPGA fabric, isolated in their required clock domains. For instance, the FMC108 module operates at 250 MSPS requiring a processing block to operate at the same frequency for optimal performance. To avoid timing errors and metastability in cross clock domain communication, register pipelining and FIFOs are used. The operation of the communication module is independent of the connected processing module, allowing for hardware FMC modules to be interchanged for various experiments while keeping the communication protocols and user interface in SPECTOR the same. Currently, data transfer rates up to 20 Mbps were achieved which were more than adequate for all experiments performed. However there is a lot of room for the optimization of the communication protocol and transfer rates of 100 Mbps and higher are achievable using standard TCP protocols. The greater transfer rates will extend the capabilities of the current system, allow it to be used as a digital oscilloscope and also increase the amount of raw data that can be stored for offline analysis.

Detector signals from the pre amplifier are fed into the FMC108 ADC module after being matched to the specific characteristics of the ADCs and processed in real time by the digital signal processing (DSP) module in the FPGA. Incoming signals are processed by a variation of trapezoidal filters based on the work of Jordanov et al. [8]. The DSP module first uses the derivative of a trapezoidal filter without a flat top and a very short shaping time (~ 100 ns) to identify a valid event and trigger the further processing of the pulse. The zero crossing of this fast pulse is used as a trigger for Pulse Height Analysis (PHA) and to record the event time and position (if a beam scanner is used). Detailed PHA is performed with a trapezoidal filter however with a much longer shaping time usually between 1 μs and 6 μs, depending on the experiment setup. The final pulse height is calculated by taking the average of the flat top part of the trapezoidal pulse and subtracting the baseline height which is calculated by a simple moving average filter. Fig. 2 illustrates the main components of the DSP module captured by Xilinx Chipscope software [9] in real time. The incoming pulse (a) is first detected by a fast filter (b); the zero crossing triggers the high resolution PHA filter (c). The final pulse height is calculated by taking the average of the flat top of the pulse (c). Upon successful calculation, the pulse height along with the time stamp and beam position is saved to the onboard DDR memory which the communication module relays to SPECTOR.

Since the whole waveform is in the digital domain, processing techniques other than PHA can be applied to extract more information from each event. Further development will include particle identification through pulse shape analysis and rise time analysis. An integrated charge analysis will also be added by the integration of each incoming pulse.

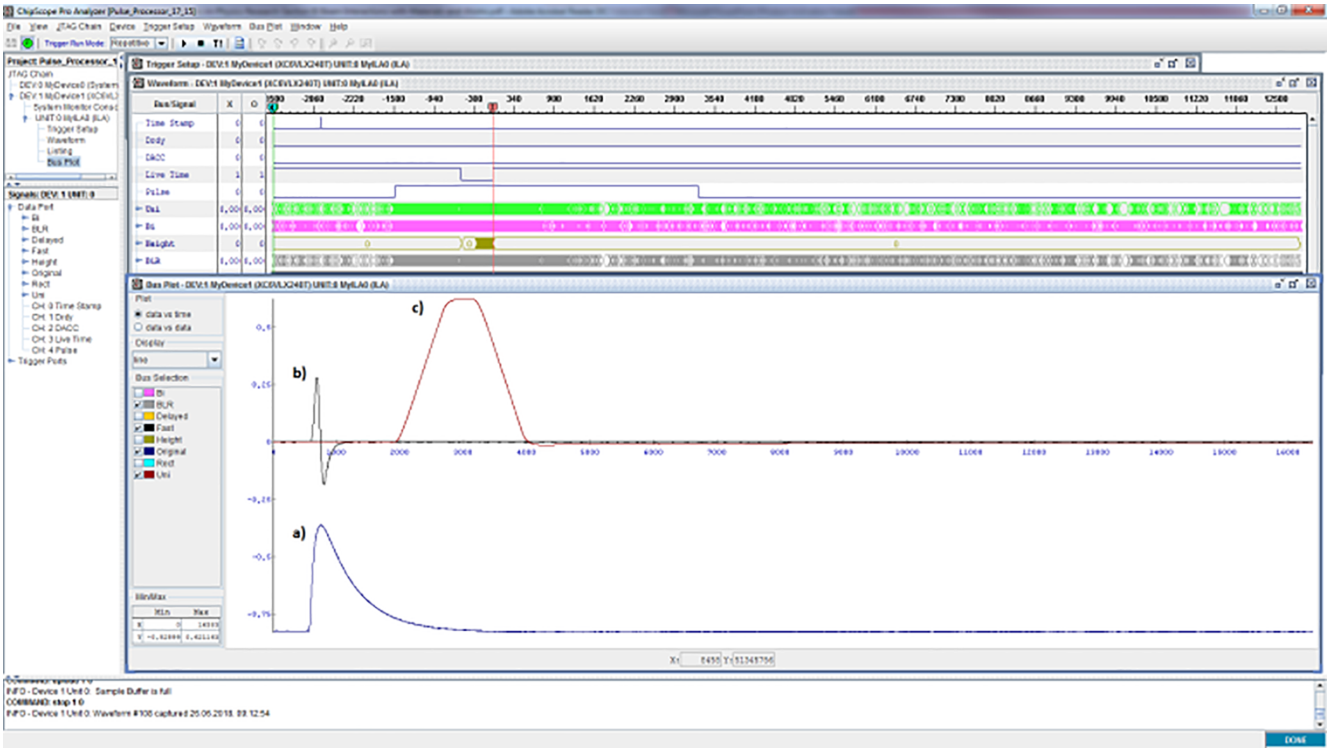
The second FMC card was specifically designed for the nuclear microprobe by providing an interface for the beam scanner, beam chopper, multi stop Time to Digital Converter (TDC), charge counter and up to 8 NIM ADC modules. Both the DSP module and the TDC module access the card depending on the experiment being performed. The TDC module in the FPGA operates at 600 MHz giving a course time resolution of 1.667 ns. This time resolution can be further refined using signal processing techniques such as interpolation [10] which will be implemented in the future. Furthermore, the module provides two outputs for beam chopping purposes. Both the duty and the frequency of the signals can be adjusted over six orders of magnitude from nanoseconds to milliseconds. An interface for NIM ADCs was also added for a seamless transition from the previous DAQ system with the additional benefits of providing a time stamp based on the leading edge of the BUSY signal. The beam scanner is controlled via two AD7248AARZ digital to analog converters (DAC) providing 12 bits of precision. The outputs of the DACs are fed through a variable amplifier which can be adjusted for the specific beam scanner used. Single channel logical outputs are also provided for triggering external instrumentation and valves. In addition to the output capabilities, the FMC card was also created to accept logic inputs. Trigger signals from Single Channel Analyzers or Constant Fraction Discriminators can be connected directly to the DAQ system. This is used for charge counting and single ion implantation experiments.

2.3. Spector

As described in [3], SPECTOR was created in collaboration with FAST ComTec for the first acquisition system used at the Rudjer Boskovic Institute microprobe. Since this initial version, SPECTOR passed through several upgrades in collaboration with IAEA Seibersdorf Laboratories and has evolved to become the standard acquisition and analysis software used throughout the laboratory. With the advent of next generation DAQ systems, the acquisition role of SPECTOR has been modified from running experiments as a server to being a client and only an interface for the user. All processing and control aspects of the experiments have been transferred to the hardware to guarantee deterministic behavior independent of the acquisition computer used and beam line location.

SPECTOR contains many powerful spectral analysis tools and functions that were specifically created for Ion Beam Analysis. However, the software was written in C with Win32 API and as it evolved with the nuclear microprobe it became very complex and fragmented. A module approach was also applied to SPECTOR by removing the direct control of DAQ system from SPECTOR and placing them in system specific dynamic-link library (DLL) file. SPECTOR accesses the DAQ hardware through generic function calls which are common to all DAQ systems. This modular approach ensures that the DAQ systems can evolve with the microprobe without losing any of the functionality developed over the years and added to SPECTOR.

Fig. 3 illustrates the new interface added to SPECTOR for interaction with the new DAQ system. Coarse/fine gain, offset and zero-pole compensation control is provided for pre amplifier signal conditioning. Energy filter shaping parameters are also entered through SPECTOR allowing for fine tuning and saving of parameters for each individual ADC. Due to the number of parameters required to be optimized, a two



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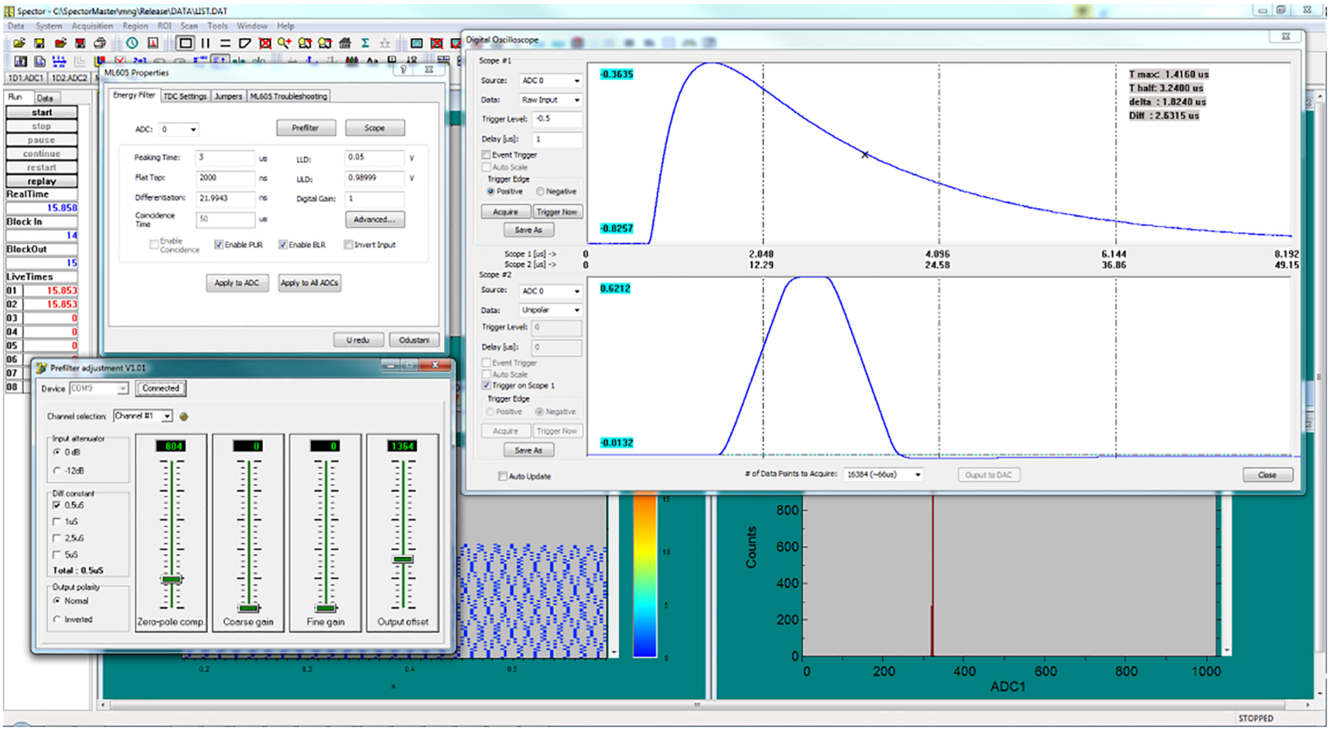
INFO - Device 1 Unit 0: Sample Buffer is full
COMMAND: stop 1 0
INFO - Device 1 Unit 0: Waveform #108 captured 25.06.2018. 09:12:54
```

Fig. 2. Real time data captured by Xilinx Chipscope software [7] of the DSP module. The incoming pulse (a) is detected by a fast filter (b) and the height is processed by a high resolution filter (c).

channel digital oscilloscope is provided for DSP configuration where signals can be visualized at any point in the processing chain from the raw input signal to the final processed pulse height calculation.

Furthermore, SPECTOR's motorized stage manipulation capabilities have been expanded to facilitate a higher degree of experiment automation. In particular the integration of SmarAct piezo based micro positioners [11] with closed-loop control allow for various lateral and rotational mapping. The control of these new stages was incorporated into the standard operating procedure of SPECTOR and therefore the user interface is independent of which motor controller is used by the experiment.



ML605 Properties – Energy Filter

ADC: 0
Peaking Time: 3 us
Flat Top: 2000 ns
Differentiation: 21.9943 ns
Coincidence Time: 50 us
LLD: 0.05 V
ULD: 0.98999 V
Digital Gain: 1
☐ Enable Coincidence ☑ Enable PUR ☑ Enable BLR ☐ Invert Input

T max: 1.4160 us
T half: 3.2400 us
delta : 1.8240 us
Diff : 2.6315 us

Fig. 3. SPECTOR with DAQ specific controls.

3. Capabilities

The upgrades described above have dramatically increased the capabilities of the DAQ system and possible applications of the microprobe. The main advances and examples of their applications are described in greater detail.

3.1. Timing measurements

For several emerging microbeam ion beam analysis techniques (e.g. MeV SIMS), there is a necessity to record exact time of the pulse creation. In addition, existence of a time stamp for each recorded event can extend the possibility to reconstruct offline different time dependences that may take place during the measurements (e.g. degradation of pulse height in IBIC).

The conventional DAQ method using NIM ADC modules was incorporated into the new system. It now allows up to 8 independent channels with the additional advantage of providing a time stamp which is triggered when the NIM ADC starts a conversion (the input signal amplitude goes above LLD). However the precision of this time stamp is limited to ~100 ns due to latch propagation delays caused by the serial interface to the NIM ADCs. Higher time stamp resolution can be achieved using the newly added signal acquisition and processing capability through the FMC ADCs where signals, straight from the pre amplifier, are processed internally in the FPGA. Using this DAQ method, the time stamp resolution is improved to 4 ns, which can be further reduced by interpolation techniques. Utilizing DSP algorithms allows for finer filter parameter tuning over a greater range to adjust the DAQ system to the specific detector – pre amplifier pair. In addition to precise configuration of pile up rejection as illustrated in Fig. 4, the system allows for finding the optimal balance between data throughput and energy resolution. With larger shaping and flat top averaging time, the output energy resolution can be increased at the cost of a larger dead time. To minimize the total dose uncertainty due to the system dead time, the system uses the fast filter trigger (illustrated in a) of Fig. 2) for event counting purposes. Acquisition presets can be also set on this event counting parameter in addition to the standard time and scanner position presets.

Time of flight experiments, such as MeV SIMS, for which a typical spectrum is shown in Fig. 5, are preformed using the TDC module in which case the input signal from a MCP is fed into DAQ system through a fast CFD. The TDC records the time between each START signal (given by the beam chopper) and MCP detector STOP signal. The time of flight between the primary ion entering the sample surface and the time of flight of each ejected molecule is saved to memory along with the beam scanner position. From the extracted information, a mass distribution spectrum can be generated along with sample surface maps illustrating the surface position of any mass of interest (upper left image in Fig. 5).

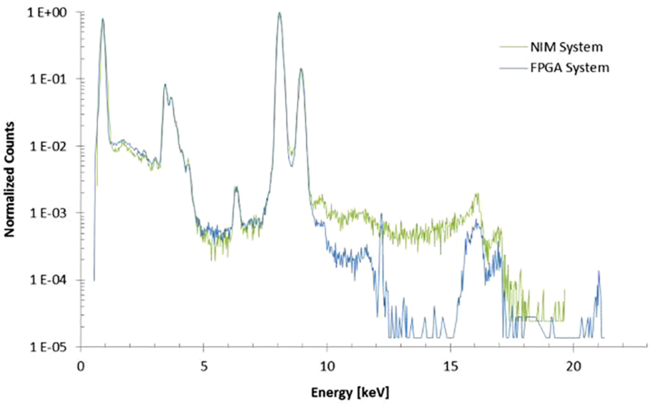


Fig. 4. Pile-Up Rejection. The peak observed at ~12 keV on the FPGA system is from a reset pulse of the SDD detector used for the experiment.

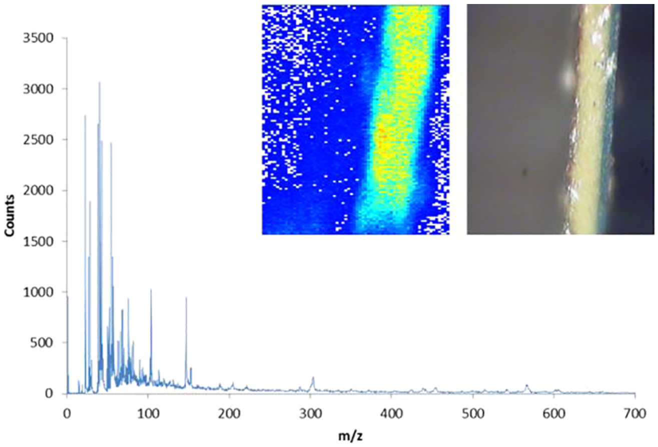


Fig. 5. MeV SIMS Experiment performed with the DAQ. The captures mass spectrum with 2D mapping and an image of sample.

The next iteration of the custom made FMC module will utilize fast comparators for the input of the MCP signal. Bypassing the CFDs, required in the current design, will further simplifying the experimental setup and enhance the timing resolution to less than 1 ns. In addition the time stamp resolution of the NIM ADCs will also be improved to 4 ns by converting the serial readout of the BUSY signal to parallel allowing the FPGA to monitor all ADCs simultaneously.

3.2. Microbeam positioning

Most of the ion beam analysis applications (including MeV SIMS as shown in Fig. 5) would not be possible without the precise control and conditioning of the beam by the DAQ system. As previously mentioned, beam pulsing/chopping is required for MeV SIMS experiments and is achieved by driving two fast high voltage switches, one for X and one for the Y axis. The opening of the beam chopper is used as the START/RESET signal for the TDC.

For 2D beam control, the DAQ system generates a scanning patter and controls an external beam scan driver/amplifier by modulating the amplitude of the signal to the device. The direction and shape of the scan patter is customizable and set by the user in SPECTOR. This is used in experiments requiring position dependent irradiations to create different regions on a single sample.

The charge counting capabilities of the DAQ system, described in the previous section, can be coupled with the beam scanner coordinate generator. This allows for the beam scanner to be advanced to the next position after a user preset amount of charge was collected per pixel. Single ion implantation experiments can be performed using this DAQ system feature.

3.3. Sample manipulation

In addition to beam scanning, 2D imaging and implantation can also be achieved by moving the sample instead of the ion beam. The DAQ system interfaces to motor controllers through a generic user interface in SPECTOR where the required live time at each pixel and grid size parameters are set. Two modes of operation are possible; a continuous mode where the scan area is repeated until the user stops the acquisition process and a single pass mode where the acquisition process is stopped automatically after a single pass.

Fig. 6 illustrates the result of a STIM-channeling experiment performed on a single crystal diamond membrane using 4 MeV Li ions. The transmission spectrums (random and oriented) along with an angular scan map are given.

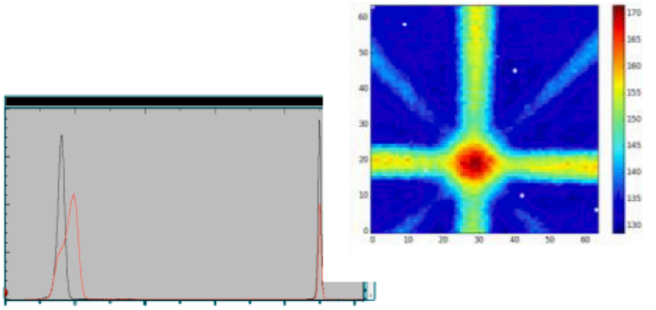


Fig. 6. Channeling STIM experiment performed by angular scanning of a sample.

4. Conclusion

The increasing complexity of modern experiments performed on the nuclear microprobe requires the precise control and synchronization of various subsystems. A versatile FPGA DAQ system was presented which implements PHA using data acquisition from the preamplifier or from NIM ADCs with beam modification capabilities and an interface for motorized sample stages. In addition to PHA, TDC measurements were performed with a chopped beam achieving a time resolution of 1.667 ns. All experiments were configured and all data was displayed using the same SPECTOR software package further simplifying the experiment setup.

However, the biggest advantage of the system is in its modular design. The modular design allows for quick development and implementation of upgrades to specific aspects of the DAQ system without impacting the operation of the whole system. This allows for the addition of new features and modes of operations to be added in a very short time frame and therefore continuously expanding the capabilities of the nuclear microprobe.

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