Potentialities of the internal target station at the Nuclotron


Abstract

The potentialities of the internal target station used in physics experiments at the Nuclotron, as well as its construction, hardware and software configurations are described. The remote control of the station is performed by means of a PC and is based on operative presentation of the magnetic field cycle, the beam parameters and the target position on screen. Consequently, the space–time trajectory of motion of a chosen target can be determined in an interactive way by an operator. During the accelerator operation the motion is carried out by means of a stepper motor.

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1. Introduction

In recent years the study of nuclear properties, using particle abrasion technique, has become one of the basic trends in nuclear interactions research [1]. The use of a superconducting accelerator of heavy ions, Nuclotron [2], built in the Laboratory of High Energies (Joint Institute of Nuclear Research, Dubna, Russia), gives new possibilities for experimental study of the processes of this type. One of the basic merits of this accelerator is the possibility to change continuously the energy of beam nuclei from injection energy, 5 MeV, up to 6 GeV.

The energy region of nuclei collisions from hundreds of MeV to several GeV per nucleon is well suited to the investigation of the transition region from proton–neutron to quark–gluon states of nuclear matter [3]. Through the use of the internal targets the Nuclotron makes it possible to carry out experiments within a consistent framework of unified experimental approach.

The technique of internal targets is widely used in physics experiments carried out with ion accelerators [4–11]. The choice of target type and its thickness is determined by the peculiarities of the task being solved. Research based on the use of internal targets is frequently applied, e.g., when

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solving problems of operational diagnostics of circulating beams [12–14], in the improvement of beam characterisation [15], in physics experiments with polarized targets [16] as well as in tasks solved by means of targets interacting with the beam at different angles. There exists a class of physics tasks for which the change to internal targets with the compensation of energy loss by ionization in comparison with external massive targets for beams with equal intensities means a significant increase of yields of nuclear reactions products. The internal targets proved to be non-replaceable for classical experiments of elastic scattering of hadrons at high energies [17], and also in experiments in relativistic nuclear physics carried out with the Nuclotron.

Motion of the target holder in the beam space as well as the choice of a target for a given experiment are accomplished by means of the stepper motor, together with optical sensors, control hardware and software. The stepper motor that is installed in a vacuum directly drives the shaft of the target holder. Given the depth and the exposure time at the appropriate moment, defined relatively to the starting instant of the accelerator cycle, the chosen target can slide into the circulating beam. The control system is realized by means of a PC connected to a CAMAC crate.

2. Internal target station

The internal target station (Fig. 1) [18] intended for physics experiments with the Nuclotron is composed of two intersecting cylinders, i.e., ion tube (1) and the cylinder (2) where the target holder carrying three targets is located.

The dimensions of the station, its construction and the thickness of the cylinder shell are optimized for registration of secondary particles using external detectors with maximum achievable spatial angle and minimum losses. Targets (3) are hung on silicon fibres of diameter 9 μm in small frames (4) in the form of letter C. The frames are attached in vertical positions to the holder (6) that is turned by means of the stepper motor (5). Several types of targets have been used in experiments, e.g., copper, gold and polyethylene foils with dimensions 4 × 8 mm and thicknesses 0.6–2.2 μm or carbon and tungsten fibres of diameters 8–10 μm. Searching for a required target for the given experiment as well as synchronization with the accelerator cycle is accomplished by electro-optical sensor.

When working with the Nuclotron internal targets, the installed scintillation detectors in the accelerator chamber are located in horizontal plane at the level of the central trajectory with registration angle of particles from 30 to 135 degrees relative to the beam direction. To determine the types and energies of secondary particles (∆T; ∆E vs. E) technique is used. The low boundary of the energy range of particles is determined by mass encountered on trajectory by registered particles. Obviously, the admissible thickness of the vacuum chamber shell should be less than the effective thickness of the first encountered detector. In our case, this should be less than 0.5 g/cm².

Stainless steel was used for the construction of the vacuum chamber. This permits operation in the condition of cryogenic temperatures. For rectilinear sections of the vacuum chamber, thin-walled pipes with electropolished interior surface have been used. To compensate temperature dilatations of segments between the electromagnetic elements of the accelerator, diaphragms made from stainless steel have been used.

Experience has shown the possibility of application of reinforced vacuum chamber shell with a thickness less than 0.5 mm, which corresponds to 0.4 g/cm². In our case, the limiting diameter of
vacuum chamber cylinder (at a pressure of 1.3 kg/cm²) is 250 mm. The internal target segment is connected to other vacuum chamber segments of the accelerator, using a dismountable vacuum junction of a conflat type with copper gaskets. The vacuum chamber is connected to other segments via bellows that enable their relative mobility.

3. Hardware configuration

The operation of the internal target station is controlled by a PC connected to a CAMAC crate. This comprises of monitoring selected accelerator parameters (e.g., intensity of magnetic field, start of working cycle, etc.), monitoring selected beam parameters (ion current, ion energy, beam profile), controlling internal target motion across the beam, as well as monitoring target radiation caused by interaction with the beam.

A block diagram of the control system of the internal target station on the level of CAMAC modules is shown in Fig. 2.

B-timer latches the starting instant of the Nuclotron working cycle. It defines the beginning of monitoring of the above mentioned parameters. The module also records the samples of both intensity of magnetic field of dipoles, and beam profile. Measurement of the beam profile is done in close proximity to the internal target station. The principle of measurement is based on ionization of residual gas caused by the beam.

ADCs 1–3 convert amplified analog signals of ion current and from detectors of target radiation, respectively. The maximum frequency of the readouts from the ADCs is 10 kHz. ADC 4 monitors the temperature of the stepper motor.
winding, which is placed in a vacuum. At a contingent exceeding the maximum allowed temperature of the motor (165°C), the operator is immediately notified, the motor is switched off and measurements are stopped. Another module that is being employed in the internal target control system, is input register. It latches 3-bit information about the initial position of the target and the working target number (1 of the 3 targets on the holder). When the working cycle is over, the targets are always returned to the initial position.

The motion of the targets is controlled by a Motor Control Interface (MCI-CAM 2.13, Institute of Physics, Budapest, Hungary). It is designed to control motors in both velocity and position. It has a program-oriented organization so that any motion algorithm can be implemented. The module makes it possible to turn the stepper motor with an angular resolution of $360°/12800$ microsteps = 0.0281°/microstep.

For construction reasons, the stepper motor (type B23.3, Arun Microelectronics Ltd., UK) is located in a vacuum. This allows the target holder to be mounted directly on the stepper motor shaft. It eliminates the influence of transmission gear upon the precision of target position. When moving the stepper motor too quickly, it is possible that fixations of the targets (very thin threads) may be destroyed. To eliminate this danger, the maximum frequency of clock pulses to control the stepper motor is limited (in our case to 4.5 kHz).

The MCI module does not contain a driver stage. However, internal control circuits of the MCI provide signals for the driver stage of the motor. In our case the stepper motor is driven by an IM 483 motor driver (miniature high performance microstepper driver — Intelligent Motion System, Inc., U.S.A.).

4. Software

With the aim of controlling the internal target station of the Nuclotron we have developed a Target program. It runs on a PC connected to a CAMAC crate with equipment as described in the previous section. The algorithm to control motion of targets is based on the operative presentation of the information about beam characteristics and targets positions on screen. The user may then define, in an interactive way, the trajectory of target motions depending on the measured physical data. The basic algorithm of the acquisition part of the Target program during one working cycle of the Nuclotron is as follows. At the beginning of the accelerator cycle, the program:

- periodically reads out the values of magnetic field B from the B-timer,
- periodically calculates the values of ion kinetic energy,
- periodically reads out the values of ion current,
- periodically reads out the beam profiles from counters installed in the B-timer,
- periodically reads out the signals from detectors of target radiation (after sliding of the operating target into the beam).

All these values are recorded in the computer memory. An example of a display of the above-mentioned measured data is given in Fig. 3. Time scales and read out periods for magnetic field, kinetic energy, ion current and beam profiles are the same. They differ from the time scale and measurement period for signals from detectors.

An operator is provided with the possibility to make a selection of working target (from three targets) as well as the starting position of the working target (points A, A', B, B' in Fig. 4). Likewise, the user may also select types, effective masses, effective charges, thicknesses of targets, rotating speed when setting starting position of working target, radius of target position, etc.

The motion of the working target in the beam (starting at the instant $t_0$, point a in Fig. 5) is based on a space–time trajectory defined in advance by the operator. In basic working mode the trajectory comprises of three parts that consist of sliding the working target into the beam, linear motion in the beam during its lifetime and sliding the working target out of the beam. The motion trajectory is defined in Fig. 5 by points $a, b, c, d$. The distance between points $b$ and $c$ (the beam lifetime) can either be given manually (using mouse) or automatically, calculated in dependence on the type of target and beam [19].
Besides the basic working mode the program allows for definition of more complicated shapes of trajectories of the target motion

- polyline (more than three parts where points are set by mouse),
- b-spline (smoothed curve where control points are set by mouse),
- analytical function. This is given by keyboard in the syntax form of mathematical expression in FORTRAN language. The permissible operators are +, -, *, /, sin, cos, exp, log, ∧, sqrt.

Time is an independent variable.

In the event that the motion trajectory turns out to be inconvenient, one can either redefine it completely or edit positions of appropriate points using the mouse. For the purposes of fine tuning part of the motion trajectory, the program makes it possible to zoom a region of the trajectory (defined by window).

The graphical part of the Target program allows the display of

- magnetic field — $B$,
- kinetic energy of ions — $E_k = A$,
- ion current — $I$,
- signals from detectors D1, D2

as 2D plots (see Fig. 3). It also allows beam profiles in 3D display contours mode to be shown. In Fig. 3 one can see the beam profile shown together with the control trajectory of target motion. On the left of the picture one can see the slice of beam profile at the instant $t_0$ that defines the start of measurements of signals from detectors D1, D2. In Fig. 3 the basic display configuration is shown. Any of the above-mentioned measurements can be

- erased from screen,
- displayed on screen,
- moved to another position on screen,
- zoomed to any size,
- listed on screen,
- written to a file,
- read from a file.

This implies that the user can create optional display configuration in accordance with the
Fig. 4. An example of display of targets positions.

Fig. 5. An example of optional display configuration.

requirements. An example of such a configuration is shown in Fig. 5. The hard copy of the screen can be printed on a B/W or colour printer or written as a bitmap to a file.

Target is an interactive menu driven program controlled by the mouse. Wherever possible, it utilizes the system of windows. It is written in C language in object oriented style that ensures its
modularity and easy adaptability. Commands are organized in a command tree. Basic nodes and windows of the command tree are presented in Fig. 6. On account of brevity we do not give all details of the tree. For full details we refer to [20] where one can find a complete description of the Target program.

All measured and calculated data, parameters, constants, chosen configurations, etc. are stored in hierarchic data structure in the memory. This enables us using one command, e.g., after completion of an experiment, all results, including configurations, to save such in a simple way on disk as one data structure. Later this information can be used to continue in the experiment, to evaluate measured data, repeat experiment etc.

This configuration structure can be also written into a local network. For other users on the network this information is available either using the same Target program or using its simplified version, Tarinfo. The Tarinfo program implements only graphics and the informational part of the Target program. In this way the graphic and text information about the experiment is available also for all interested users on a local network.

5. Experimental setup and results

During the starting period of the beam acceleration cycle, the target is located outside of the working beam aperture. After achieving the required energy of beam particles, the target starts to move across the beam. It moves in this direction until the magnetic field of the accelerator starts to decrease. The target then returns back to its starting position. For all that, during the motion of the target in the beam one can reach maximum interaction time of the beam with target as well as full exploitation of beam intensity (maximum luminosity). Adhering to the aims of the experiment, the space-time trajectory of the target motion is set according to the particles type, beam energy and target material. For illustration purposes, in Fig. 7 we present the dependence of beam intensity recorded in time with and without the use of the target.

The above-described internal target station together with its control system were used in an experiment in research of meson production in interaction of deuteron beam with the nuclei of gold at beam energy 2.1 GeV. The block diagram of the experimental setup is shown in Fig. 8. The setup is

![Fig. 6. Basic command tree of the program target.](image-url)
located in the Nuclotron tunnel in one of the “warm” gaps of the accelerating structure. The detectors TC1 and TC2 serve as a time-of-flight spectrometer with basis of 1200 mm and time resolution about 250 ps. The distance from the studied target to the detector is 300 mm. The counters are made from slices of standard plastic scintillator with sizes $50 \times 50 \times 5 \text{ cm}^3$ (TC1) and $160 \times 160 \times 20 \text{ cm}$ (TC2). In order to compensate the time shift caused by non-zero time-of-flight of scintillation photons to photocathode during particle passing through scintillator, in the detector TC1 two photomultipliers of XP2020 type installed on opposite sides of the scintillator are used. In the detector TC2, four multipliers FEU-87 installed on all four sides of the scintillator are used. The time and amplitude analysis of the signals from all four photomultipliers are performed independently.

The spectrometer of full absorption energy (ST) is used for the definition of full kinetic energy and particle mass identification. The spectrometer consists of 14 plastic detectors with thicknesses from 20 to 40 mm. The flash of light caused by passing of charged particles through detectors is transmitted to photomultipliers by means of fibre-optic-based light guides. In each detector the ionization losses caused by passing of the registered particles through material are measured, i.e., the course of the Bragg curve is determined. When measuring energy loss in each detector with resolution about 15%, using calculations carried out by means of the program GEANT 3.21, one can conclude that precision of the order 3% in the definition of particle energy can be obtained.

Fig. 7. Interaction of the target (thin thread) with internal nuclotron beam: 1 – magnetic field, 2 – beam intensity without the use of the target, 3 – beam intensity with the use of the internal target, 4 – moment when the target starts to slide into the beam.

Fig. 8. The installation layout at the Nuclotron internal target.
The energy intervals of measurements are: for positive and negative pions 40–150 MeV, K\(^+\) mesons 60–280 MeV, protons 80–320 MeV. Anticoincidence detector AC, installed at the end of the spectrometer serves for limitation of the effective interval of charged particle energies up to the area of full absorption of ionization losses in the spectrometer material.

In Fig. 9 one can see an example of the two-dimensional spectrum (kinetic energy vs. time of flight) for secondary particles measured at an angle of 73° relative to the beam direction. In the two-dimensional plot one can observe the separation of particles on masses. This permits the carrying out of separation analysis of meson spectra in deuteron–nuclear interactions. The results of the experiment were published in Refs. [21,22].

Besides the experiment described so far around the internal target station there exist also other experimental setups. Experiments utilizing these setups and the internal target station were published in Ref. [23].

6. Conclusions

One can conclude that the large scope of possibilities provided by the Nuclotron, the internal target station and the wide assortment of detectors make it possible to carry out a broad scale of experiments in the field of relativistic nuclear physics. Polyethylene and gold foils were used for investigation of \(\gamma\)-quanta production, \(\pi\) and subthreshold \(k\)-mesons as well as different fragments starting with protons and ending with isotopes \(^6\)He [21]. Within the framework of SPHERE collaboration, the study of inclusive spectra of cumulative protons in the region of fragmentation of the target nuclei [24], and also the measurement of geometric dimensions of the typical region of their inception [23] were performed. The internal targets technique enables the study of the generation of fast neutron beams using compact, practically point (with negligible size) targets, to optimize this process and to study its spectral characteristics [25].

The internal target station is exploited also for the investigation of nuclotron beam parameters. At the end of 1998, the first experiment on the resonance excitation of an accelerated beam, which is needed for its slow extraction was carried out (Fig. 10).

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References