Eurasian Journal of Physics and Functional Materials

2019, 3(1), 46-52

Current status of the new fragment separator ACCULINNA-2 and the first-day experiments

A.V. Gorshkov[1,2,*], S.G. Belogurov[1], A.A. Bezbakh[1,2,3], D. Biare[1], W. Beekman[4], V. Chudoba[1,3], A.S. Fomichev[1,5], M.S. Golovkov[1,5], E.M. Gazeeva[1], L.V. Grigorenko[1,2,6], G. Kaminski[1,7], S.A. Krupko[1,2], B. Mauyey[1,2,8], I.A. Muzalevsky[1,2], E.Yu. Nikolskii[1,2], Yu.L. Parfenova[1,9], A. Serikov[1], S.I. Sidorchuk[1], R.S. Slepnev[1], P.G. Sharov[1,2], G.M. Ter-Akopian[1,5], R. Wolski[1], B. Zalewski[1,7]

[1]Joint Institute for Nuclear Research, Dubna, Russia

[2]National Research Center "Kurchatov Institute", Russia

[3]Institute of Physics, Silesian University in Opava, Czech Republic

[4]SIGMAPHI, France

[5]Dubna State University, Russia

[6]National Research Nuclear University "MEPhI", Russia

[7]Heavy Ion Laboratory, University of Warsaw, Polanda

[8]L.N. Gumilyov Eurasian National University, Kazakhstan

[9]Skobeltsyn Institute of Nuclear Physics, MSU, Russia

E-mail: agorshkov@jinr.ru

DOI: **10.29317/ejpfm.2019030106**
Received: 14.03.2019 - after revision

The commissioning of the new fragment separator ACCULINNA-2 at FLNR JINR is accomplished. The separator is destined to expand the possibilities in studies of dripline nuclei performed with the exotic secondary radioactive ion beams (RIBs) at energies of (5 – 50) AMeV. The projected high transmission and purification level were confirmed experimentally for a number of RIBs in the last two years. The ACCULINNA-2 setup will become a backbone facility at FLNR for the research in the field of light exotic nuclei. This report shows the current status of the separator, describes the obtained RIBs parameters and first experiments as well, provides the overview of the developing detection, monitoring and control subsystems.

Keywords: fragment separator, secondary beams, exotic nuclei.

Introduction

The new fragment separator ACCULINNA-2 in the Flerov Laboratory of Nuclear reactions, JINR Dubna is in commissioning phase since 2016 [1, 2]. The separator and a part of the primary beam line were designed and built in collaboration with the SIGMAPHI company, France [3-5]. It is 36 meters long achromatic separator consisting of two 45-degree dipole magnets, 14 quadrupoles, eight multipoles (three octupoles and five sextupoles) and four steering magnets.

The high intensity primary beams are delivered by the U-400M cyclotron to the rotating production target module installed in the first intermediate focal plane F1 (see Figure 1) to produce radioactive ion beams in fragmentation reactions via the in-flight method.

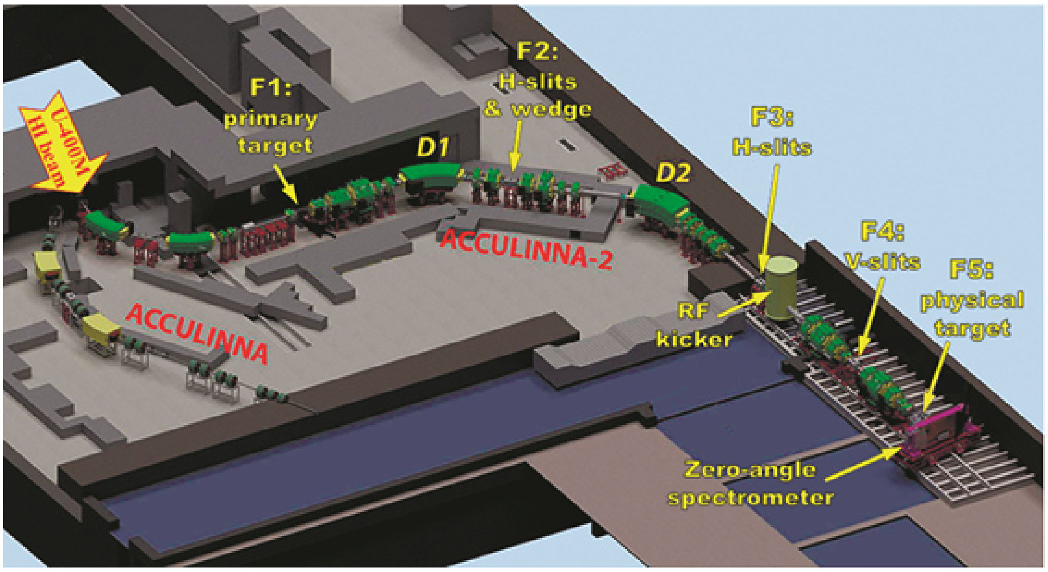

Figure 1. The ACCULINNA-2 layout at U-400M cyclotron cave. The separator focal planes are indicated by F1-F5. The concrete radioactive protection, the dipole magnet of zero-angle spectrometer and planned RF-kicker are also shown.

The target module integrates a vacuum chamber with a water cooled beryllium target mounted on rotating magnetic liquid feed through and a set of water-cooled diaphragms. The target module is designed to work with heating power up to 2 kW. Using the combination of magnetic analysis and energy losses in achromatic wedge degrader located at the intermediate dispersive focal plane F2, the secondary ions are separated in flight. Then, the secondary beam is delivered into the low-background experimental area with full particle-by-particle identification.

Separator equipment and scientific tools

In order to become a fully-featured measuring complex for the studies of exotic nuclei, ACCULINNA-2 should be equipped with numerous devices. The separator equipment and scientific tools for the ACCULINNA-2 facility are under active development. Some parts are already mounted and used in first scientific experiments, some of them are still in R&D or production stages.

For primary beam control in addition to Faraday cups two primary beam profile monitors, mounted on pneumatically actuated motion feed throughs, are provided for precise measurements of primary beam shape.

To adjust the momentum acceptance of fragment separator, the motor driven horizontal slits (H-slits) in F2 and F3 are installed. Additional vertical slits (V-slits) will be placed in the focal plane F4 during the RF-kicker installation (see section 1.3.1). Stepper motors provide 0.1 mm slits gap accuracy. The slits have changeable cranks optimized for usage with proton- or neutron-reach beams.

RIB diagnostic instruments. The RIB diagnostic system of the ACCULINNA-2 complex consists of time-of-flight (ToF) and tracking detectors. For precise particle identification, two ToF scintillation detectors are installed in F3 and F5 focal planes of ACCULINNA-2 at a distance of 12.3 meters. Depending on the experimental program, these detectors can be equipped with organic scintillators (e.g. BC404) with a thickness down to 25 μm with an active area of 60 mm in diameter. Each scintillator is coupled with four Hamamatsu R7600-200 photomultiplier tubes (PMT). In the case of scintillator thickness of 125 μm, a time resolution of 100 ps (sigma) can be obtained.

Two multi-wire proportional chambers (MWPC) serve as tracking detectors. In current experiments old type of MWPCs with (32×32) wires and 1.25 mm wire distance are used [6]. These detectors operate at atmospheric pressure of CF_4 and CH_4 gas mixture with a ratio 9 to 1. The signals registered by the wires, passing through the low level discriminators (LLD) are recorded by homemade CAMAC registers. The new fragment separator ACCULINNA-2 has bigger image size in the final focal plane compared to the previous generation one. Production of new multi-wire proportional chambers with (48×48) wires is nearly finished and will be tested soon with Mesytec MQDC32 read out.

Physical targets and particle detectors. Studies of exotic nuclei at the two Dubna fragment separators are mainly carried out with cryogenic targets (all stable helium and hydrogen isotopes, including even tritium). The available cryogenic target cells are of 25 or 30 mm in diameter with nominal thicknesses from 0.4 to 6 mm, have modular construction and can have a thickness up to 10^{22} at/cm^2. The cells have stainless steel windows with thickness from 6 to 9 μm.

Each cryogenic target is equipped with automated gas system with safety interlocks and cryogenic temperature stabilization. The system will be implemented to the common ACCULINNA-2 control system and will prevent the possibility to blow up foils of cryogenic cells, will ensure safe usage of cryogenic target in any emergency situations and will decrease losses of rare and expensive gases.

In collaboration with Federal State Unitary Enterprise Russian Federal Nuclear Center (FSUE RFNC - VNIIEF) in Sarov, the ACCULINNA-2 team started development of a new tritium target complex. The maximum volume of the liquid or solid tritium will be about 1 cm^3, which corresponds to an activity about 2.7 kCi. Whole tritium gas system will be mounted on top of a cold head in specially designed chamber with radiation safety monitoring. The filling and maintenance of the tritium gas system will be performed in specially designed room at the second floor of the F5 area of ACCULINNA-2 with special ventilation, radiation monitoring and access control. First test of a new tritium target complex is planned in 2021.

The ACCULINNA-2 team has a full set of charged-particle detector telescopes. We have annular and square shaped single sided and double sided silicon strip detectors with thickness from 20 μm to 1.5 mm. The CsI(Tl) segmented arrays with square and annular shape are complementing well with the corresponding Si telescopes. In addition, 40 neutron detection modules, based on stilbene crystals with corresponding PMTs are assembled into a “neutron wall” [7] can by effectively used for a broad variety of experiments.

Data Acquisition System. All particle detectors and RIB diagnostic system of ACCULINNA-2 with appropriate electronics are implemented to one distributed multi-processor data acquisition (DAQ) system based on Multi Branch System (MBS) [8]. The main DAQ combines VME crates with installed CES RIO4 or RIO3 VME controllers [9], distributed along the beam line. One VME crate has a CVC-GTBV4 VME-CAMAC brunch [10] to read out old school electronics. Each controller operates under LynxOS real-time operation system. All crates are connected to the common trigger bus via TRIVA modules [10] a for event synchronization. An additional Linux based MBS event builder server allows to merge all data flows from each VME controller into a single data stream of reconstructed events. Flexible user readout interface of MBS allows to implement almost any configuration of detectors spaced from each other by more than the length of existing fragment separator.

The processing of the beam profilometer signals is carried out by two modules of the 32-channel readout system for low-current Profile Acquisition Digitizer (POLAND) based on ASIC current-to-frequency converters [11]. The MBS is responsible for data collection and management. The beam profile monitoring is constructed as an independent subsystem but can be easily integrated into the main data acquisition system of ACCULINNA-2.

The online monitoring and visualization of experimental data proceed by the Go4 analysis Framework [12]. For further offline data analysis ROOT or any ROOT-based frameworks can be easily applied.

Development of future subsystems

RF kicker. The purification level of ACCULINNA-2 separator is typically sufficient for preparation of quite pure beams in the final focal plane F5 in the case of neutron-reach fragmentation products. The neutron-deficient RIBs suffer from large number of contaminations. To deal with it, the vertically deflecting radio-frequency (RF) kicker [13] will be installed in 2019 at a distance of 25 meters from production target just after the achromatic focal plane F3 (see Figure 1). It has a 70 mm gap between electrodes and operates at a maximum field of 15 kV/cm with a frequency from 15 to 22 MHz. RF kicker phase correction has synchronization with cyclotron the RF or with a signal from pick-up device installed in a primary beam line. The most important projected parameters of the RF kicker together with the example of its expected operation can be found in [1] for the case of ^{28}S isotope.

Zero-angle spectrometer. The ACCULINNA-2 experimental complex is devoted to studies of exotic nuclei and their decay products. In 2017 at the ACCULINNA-2 facility a dipole magnet for zero-angle spectrometer was installed for identification of different charged particles and for measurements of their energies and angles (see Figure 1). It is a 20 tones open-frame magnet with a 180 mm gap. The reaction products enter the front aperture and are bent by the well mapped magnetic field. Thus their magnetic rigidities, and hence their momentum values, can be defined, provided that their individual trajectories are measured accurately. The tracking detectors of ACCULINNA-2 provide 1.25-mm accuracy in the hit positions of RIB nuclei on the physics target. It means that, to use this dipole magnet as a zero-angle spectrometer, it should be equipped by specially designed position-sensitive detectors, which will provide similar precision in measuring the coordinates of particles at the entrance and exit of the magnetic field. It is also important to use a ToF detector installed at the exit border of the magnet. This will give access to the velocity measurement and, taking into account the measured momentum values, to the determination of the particle mass. The development of these detectors and appropriate electronics are in progress.

Basic parameters of RIBs obtained at ACCULINNA-2

The projected high transmission and purification level of ACCULINNA-2 were confirmed experimentally in a set of tests with ^{15}N [1, 2] and ^{11}B primary beams in the last two years. In the last year, the fragment separator was tuned for the ^{8}He secondary beam produced in fragmentation reaction of ^{11}B with energy of 33.4 A MeV on 1-mm-thick beryllium production target placed in the F1 focal plane. The secondary beam was cleaned by natural beryllium 1-mm-thick achromatic wedge degrader (angle 2 mrad), located at F2.

Time of flight, energy losses and spatial distribution of the reaction products were registered by the ACCULINNA-2 RIB diagnostics detectors. The ToF plastic scintillators had 250 μm thickness. Typical two-dimensional plots of beam spot measured in the final focal plane F5 and the ΔE-ToF identification plot obtained when the separator was tuned for the ^{8}He (26.1 AMeV) secondary beam are shown in Figure 2. The slits at F2 were fully opened (± 68 mm) and at F3 the slit gap was ± 15 mm.

At the F5 focal plane of the ACCULINNA-2, the RIB spot size was (16×11) mm, as shown in Figure 2, while the beam size on the production target was 7 mm in diameter. Under these conditions a beam purity of 87% was obtained. The measured ^{8}He intensity at F5 was $5.8 \cdot 10^{4}$ 1/s with a 1 pμA ^{11}B primary beam on the production target, which is agreement with a LISE++ [14] simulation. The discrepancy between experiment and prediction, which is about a factor of two, can be explained with differences in the definition of the production mechanism at intermediate energies for the reaction of ^{11} B (33.4 AMeV) on a Be target.

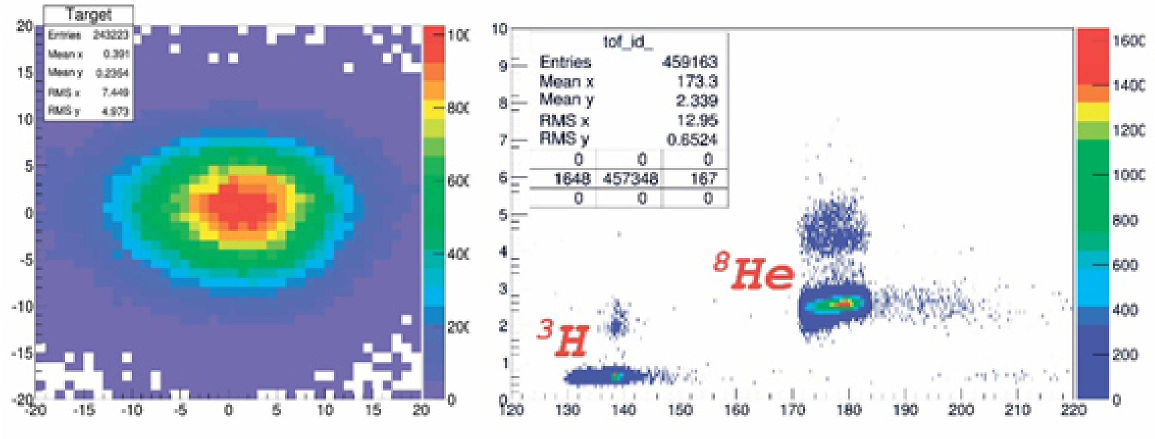

Figure 2. The profile of ^{8} He secondary beam at the F5 plane obtained via a MWPC (left panel). The identification plot resulting from the measurement of the energy loss of the ions in a thin plastic scintillator vs. the time of flight (right panel). The results were obtained with 1 mm beryllium target and Δ p/p = 7 % at F2.

First-day experiments

The first full-scale experiment at the ACCULINNA-2 fragment separator aimed at studies of elastic and inelastic scattering of ^{6} He nuclei at a deuterium target and was done in March 2018. The average intensity of the ^{6} He beam (E = 26 AMeV) was about 10^{5} 1/s. The angular distributions were measured in a wide range from 25 ° to 130 ° in the center-of-mass system. The data were taken in three runs by two telescopes, namely, a d-telescope and a He-telescope, which worked in coincidence mode. The obtained angular correlations of particles in the d-telescope with ^{6} He in the He-telescope allowed the separation of the elastic channel on the deuteron and the proton (as a background). The analysis for obtaining the final cross-section is ongoing.

In October 2018 a first test run aiming at a study of the super heavy ^{7}H produced in the transfer reaction d(^{8}He,^{3}He)^{7}H with a 26 AMeV ^{8}He secondary beam on deuterium gas cryogenic target was performed. Two silicon telescopes consisting of 22 μm and 1-mm-thick position-sensitive detectors were used to detect ^{3}He recoil nuclei. The energies and positions of tritons from the decay were $^{7}H \rightarrow$ t+4n measured at forward angles by a Δ E-E telescope consisting of a double-sided 1.5-mm-thick silicon strip detector and a CsI(Tl)/PMT array (4 by 4 units). The data analysis is in progress.

In December 2018 a study of low-energy states of ^{10} Li in the reaction d(^{9}Li,p)^{10}Li → ^{9}Li+n reaction with 30 AMeV ^{9} Li beam on deuterium cryogenic target is planned. The key point of this measurement is the use of the "combined mass" method based on detection of protons in backward direction in coincidence with fast neutrons emitted at forward angles. The neutrons will be measured by a multi-detector array (5-cm-thick stilbene crystals with diameter of 8 cm coupled with 3 inch PMTs) which was recently commissioned and tested [7].

Conclusion

The first radioactive beams were produced at the ACCULINNA-2 fragment separator at the U-400M cyclotron complex. The basic ion-optics characteristics of the ACCULINNA-2, as described in the Letter of Intent [13], were confirmed experimentally for a number of RIBs. In 2018 first-day experiments devoted to the study of ^{6}He+d scattering and to the search for the ^{7}H nucleus were carried out. Several experiments are planned to be performed at this facility in the near future, including studies of the ^{7}H, ^{10}Li, ^{17}Ne and ^{26}S exotic systems. New separator equipment and scientific tools for ACCULINNA-2 are under active development.

Acknowledgments

The work is carried out with partial financial support of the Russian Science Foundation grant No. 17-12-01367 and FAIR-Russia Research Center.

References

[1] A.S. Fomichev et al., Eur. Phys. J. A **54** (2018) 97.
[2] A.A. Bezbakh et al., EPJ Web of Conferences **177** (2018) 03001.
[3] L.V. Grigorenko et al., Nucl. Phys. News **24** (2014) 22.
[4] S.A. Krupkoet et al., EPJ Web of Conferences **66** (2014) 11021.
[5] W. Beeckman et al., Proc. 13th Intern. Conf. on Heavy Ion Accelerator Technology, Japan (2015).
[6] A.M. Rodin et al., Nucl. Instrum. Methods B **204** (2003) 114.
[7] A.A. Bezbakh et al., Instrum Exp Tech **61** (2018) 5.
[8] http://www.gsi.de/mbs.
[9] http://www.ces.ch.
[10] https://www.gsi.de/en/work/research/experiment_electronics.htm.
[11] S. Lochner et al., GSI Scientific Report **2014-1** (2013) 385.
[12] http://go4.gsi.de.
[13] A.S. Fomichev et al., JINR Communication E13-2008-168 (2008).
[14] O.B. Tarasov, D. Basin, Nucl. Instrum. Methods B **266** (2008) 4657.