JOINT INSTITUTE FOR NUCLEAR RESEARCH
Flerov Laboratory of Nuclear Reactions

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Light Radioactive Beams production at the ACCULINNA-2 separator

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Abstract

The ACCULINNA separator is one of the most important light radioactive ion beams at western part of Europe. The facility is operating since 1996. High intensity primary beams of ^{7}Li, ^{11}B, ^{13}C, ^{15}N and ^{18}O with the beam energy ranging between 32 and 50 AMeV are delivered by the U-400M cyclotron. In-flight fragmentation technique is used for the production of secondary beams of exotic nuclei with energy about 20-50 AMeV. The availability of radioactive beams and cryogenic target cell allows us to study the structure of neutron halo nuclei by transfer reactions as well as to produce unknown unstable nuclei beyond the neutron drip line.

As a next step of an upgrade of the ACCULINNA, in the years 2011 – 2015, a new improved in-flight fragment separator has been constructed. The ACCULINNA-2 separator is offering high intensity Radioactive Ion Beams with Z=3÷36 in the lowest energy range (30-60 AMeV) attainable for in-flight separators.

In March 2017 year the first experiment at the ACCULINNA-2 separator has been carried. During my practice at Joint Institute of Nuclear Research I the main goal was to analyze data collected in this experiment.

Introduction

One of the principal fields of research at Flerov Laboratory of Nuclear Reactions is the Radioactive Ion Beam (RIB) research. The ACCULINNA is one of the DRIBs (Dubna Radioactive Ion Beams) facilities. The separator is working with full load since 1996 year. The scientific results obtained at the facility are recognized by nuclear physics community, which is reflected mostly by the number of publications and conference proceedings.

The light radioactive ions DRIBs facility is represented by the U400M cyclotron and the in-flight separator complex. The U-400M cyclotron delivers beams of light ions at the energy (30-50 AMeV) to the ACCULINNA separator production target. The layout of the ACCULINNA separator is presented in figure 1.

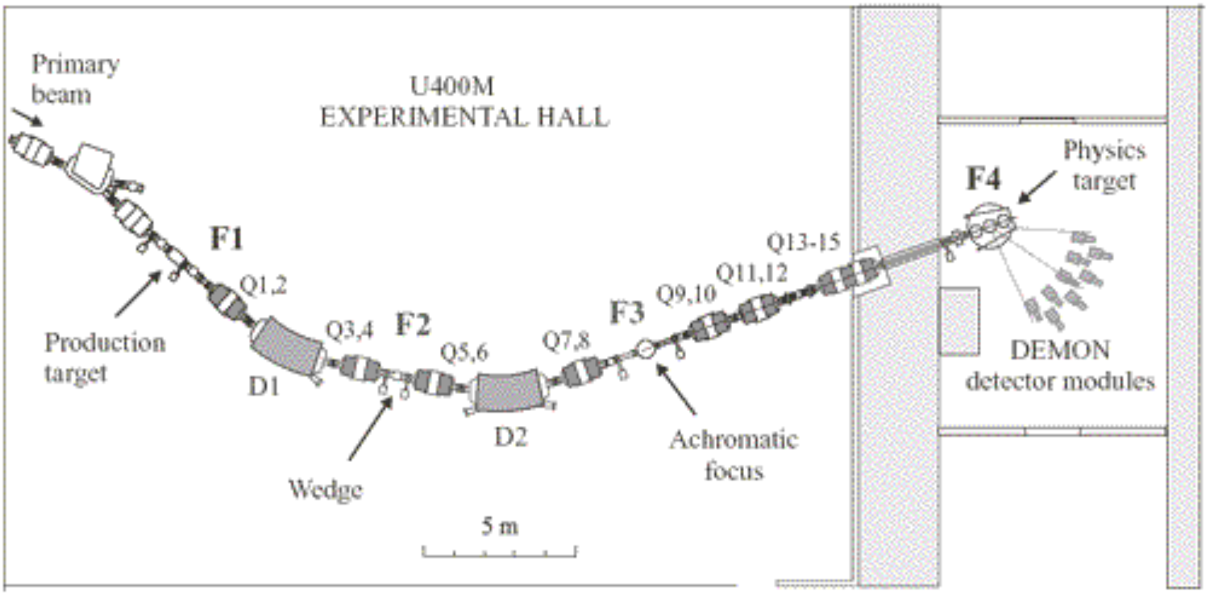

Figure 1. Layout of the ACCULINNA separator.

The achromatic ion-optical system is optimized for focusing fragments emerging from the production target placed in the object plane F1, to the achromatic focal plane F3. The desired secondary beams are separated by the magnets D1 and D2 according their magnetic rigidity ($B\rho$). A wedge-shaped degrader installed in the intermediate dispersive focal plane F2 is used for additional separation of the fragments according to the energy loose. Typically, a beryllium is used for a target and a wedge material with the thickness in the range from 55 to 370 mg/cm^2. The function of the wedge is to increase the beam purity as well as "effective" intensity of the radioactive beam. The application of the wedge shape degrader gives a gain of the secondary beam intensity by a factor of 1.2. The maximum increase (by a factor of 1.5) was obtained for a 8 AMeV ^{8}He beam delivered to focal plane F3.
At the achromatic focal plane F3, the first time of flight (TOF) detector is installed. The first upgrade of ACCULINNA was the extension of the beam line. The target intended for secondary beams was moved from the plane F3 to the plane F4 located beyond the 2-m concrete wall of the U- 400M hall. As a result, the radiation background around the reaction chamber was reduced drastically. An important improvement was the possibility to work with neutron detectors in the proximity of the reaction chamber. Another upgrade consisted in the increase of the secondary beam was by capture of solid angle. This was reached by means of cross-shaped vacuum pipes installed in quadrupole lenses Q1– Q15. Finally, by focusing the primary beam to a 5-mm beam spot located on the production target located/placed/installed at the F1 focal plane [1] the transmission of the primary beam was improved to get a 90%.

After a decade of successful operation of ACCULINNA, the project of a new in-flight separator ACCULINNA-2 at the U-400M cyclotron in FLNR, was proposed to upgrade the research done at the existing separator ACCULINNA [2]. In 2016 year the new separator has been commissioned. Using the primary beams which are available at the U400M cyclotron – the energy in the range of 30-60 A MeV and 3 ≤ Z ≤ 36, the new facility should deliver a wide range of RIBs of light nuclei. It is optimized for large RIB intensities and high precision studies of direct reactions populating nuclear systems near and beyond the drip lines through sophisticated correlation experiments [3]. The main scheme of ACCULINNA-2 and the comparison of the characteristics of the existing in-flight separator are presented in figure 2 and table 1, respectively.

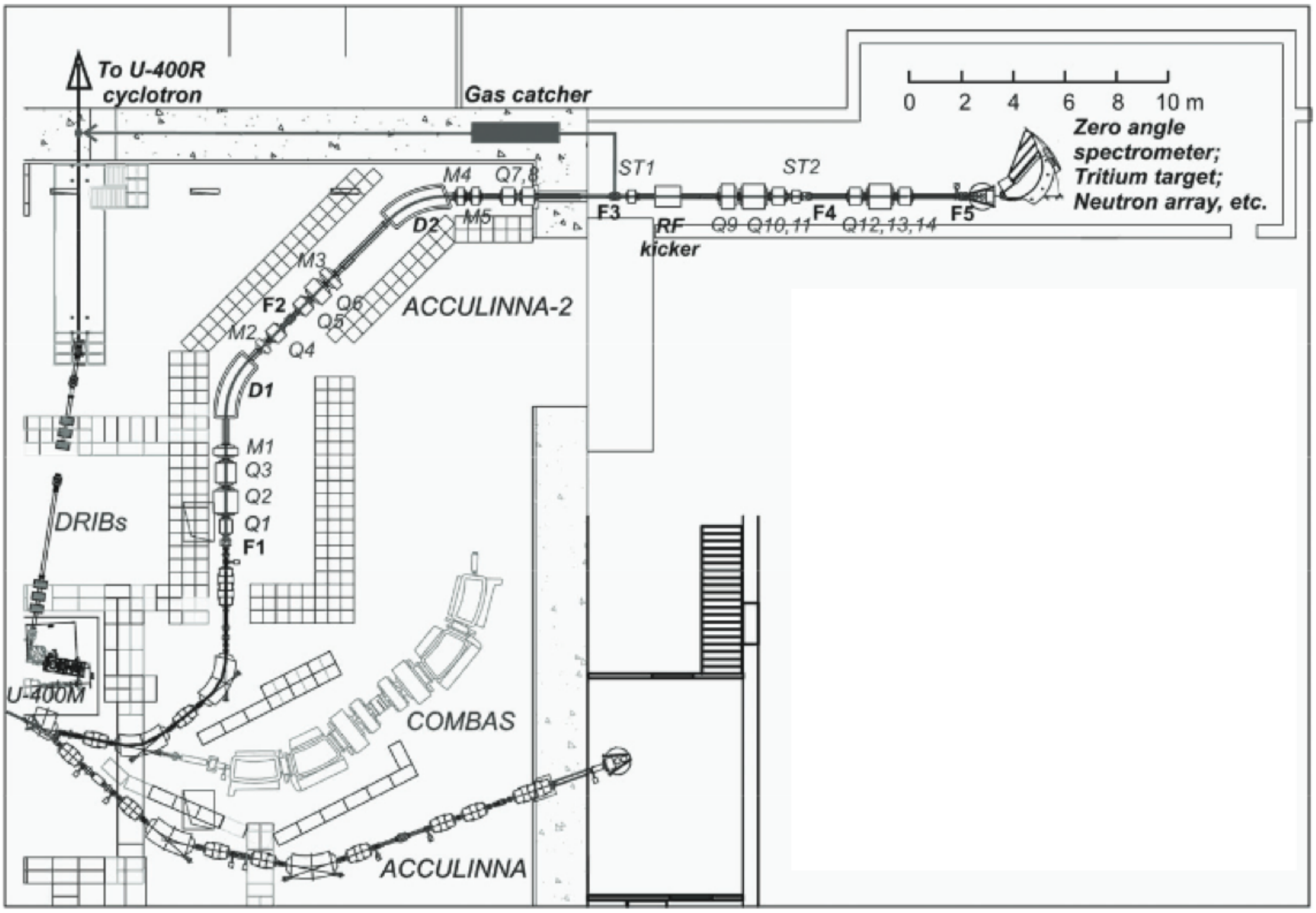

Figure 2. Scheme of part of the U-400M cyclotron hall with ACCULINNA and ACCULINNA-2 separators.

Table 1. Characteristics of in-flight separators. ΔΩ and Δp/p are angular and momentum acceptances, Rp/Δp is the first-order momentum resolution for 1mm size object.

	ACC/ACC-2, FLNR JINR	RIPS/BigRIPS, RIKEN	A1900, MSU	FRS/SuperFRS, GSI	LISE3, GANIL
ΔΩ[msr]	0,9/5,8	5,0/8,0	8	0,32/5,0	1
Δp/p [%]	±2,5/±3,0	±3,0/6,0	±5,5	±2,0/5,0	±5,0
Rp/ Δp	1000/2000	1500/3300	2915	8600/3050	2200
Bρ [Tm]	3,2/3,9	5,76/9,0	6	18/18	3,2-4,3
Length [m]	21/38	27/77	35	74/140	19 (42)
E [AmeV]	10÷40/6÷60	50÷90/350	110÷160	220÷1000/1500	40÷80
Additional RIB Filter	No/RF-kicker	RF-kicker/ S-form	S-form & RF-kicker	S-form/ Preseparator	Wien filter

ACCULINNA-2 does not compete with other separators but definitely complements the scope of ongoing research in other research centers around the world. The comparison of the range of masses and the energies of studied nuclei at ACCULINNA-2 with other separators is presented in figure 3.

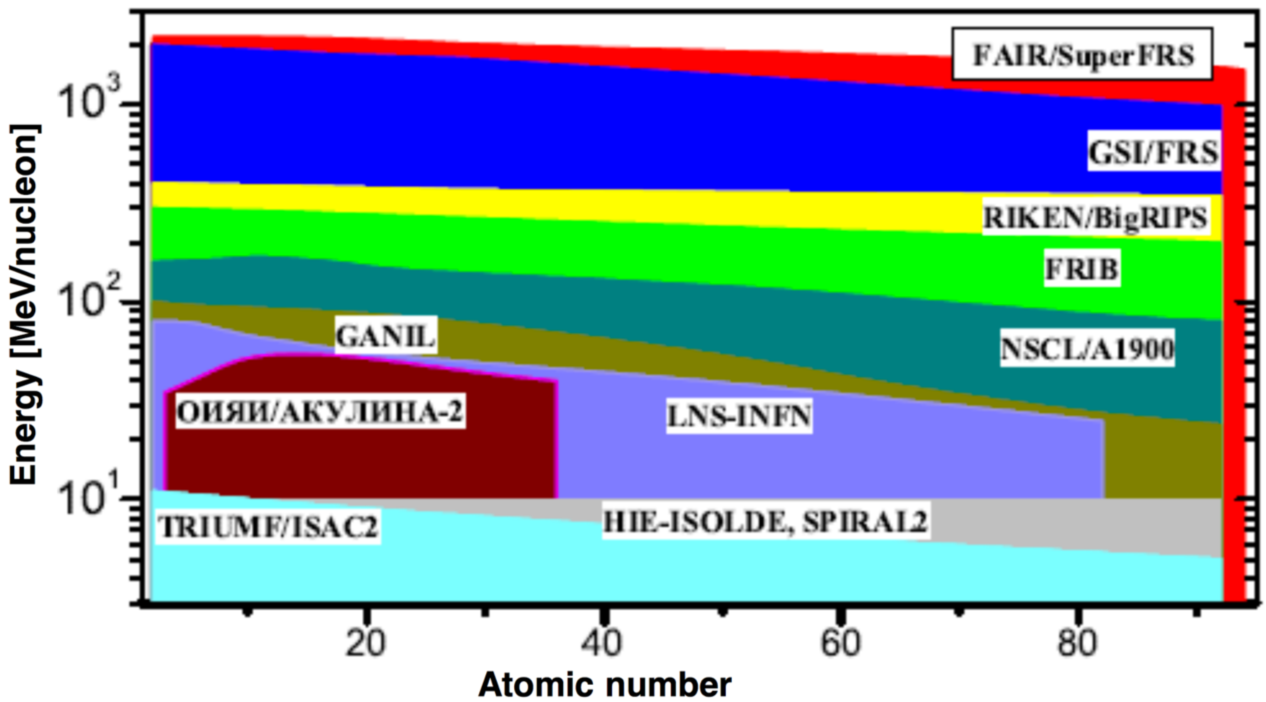

Figure 3. The range of mass and the energies of the studied nuclei at ACCULINNA-2 compared to other separators.

Another upgrade of ACCULINNA-2 is installation of the zero degree spectrometer. The scheme of the zero degree spectrometer and zero-degree spectrometer magnet before installation is presented in figure 4. The zero degree spectrometers and particle tracking systems are typically used in studies of nuclei at the borders of nuclear stability. Sometimes, it is important to use more than one reaction mechanism to study the same nucleus because different reactions can probe different parts of the nuclear structure. The most commonly used reaction mechanisms are such as transfer with stable or radioactive beams, knockout and breakup reactions. There many experimental setups that are being used for such types of experiments at the rare isotope beam facilities around the world [4]. They all consist of a neutron array located around 0° with respect to the beam axis and a dipole magnet that is used to bend the charged particles off the beam axis and into position and energy sensitive detectors. In case of decay of studied nuclei an useful tool for the full reconstruction of the decay energy of an unbound state is invariant mass analysis. As well invariant mass analysis approach is very common experimental technique in experiments at ACCULINNA [5], and zero degree spectrometer will open a new possibilities for nuclear structure studies.

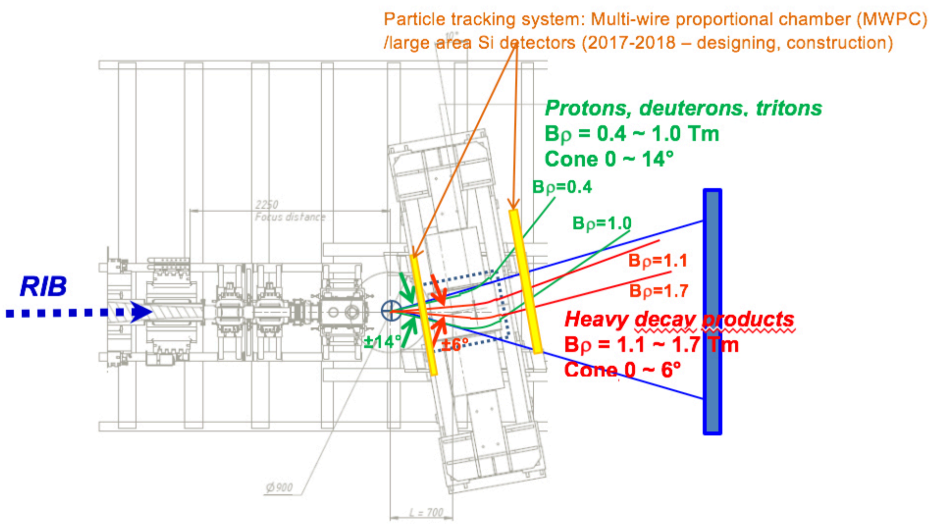

Figure 4. Scheme of the zero-degree spectrometer.

Figure 5. Zero-degree spectrometer magnet before installation.

In March 2017 year, the first experiment with ACCULINNA-2 separator has been carried out. The goal of the experiment was to check ACCULINNA-2 beam optics system and comparison of the secondary beams intensities with the theoretical predictions. The reaction of ^{15}N (49.7 AMeV) beam at 1 pnA (7enA) and ^{9}Be (2 mm) target has been performed. The analysis of the collected data are in progress.

Methods

The data from the first experiment at the ACCULINNA-2 were processed. The format of the data has allowed to work with them freely with the ROOT data analysis environment. An example of the ROOT analysis window is presented in figure 6.

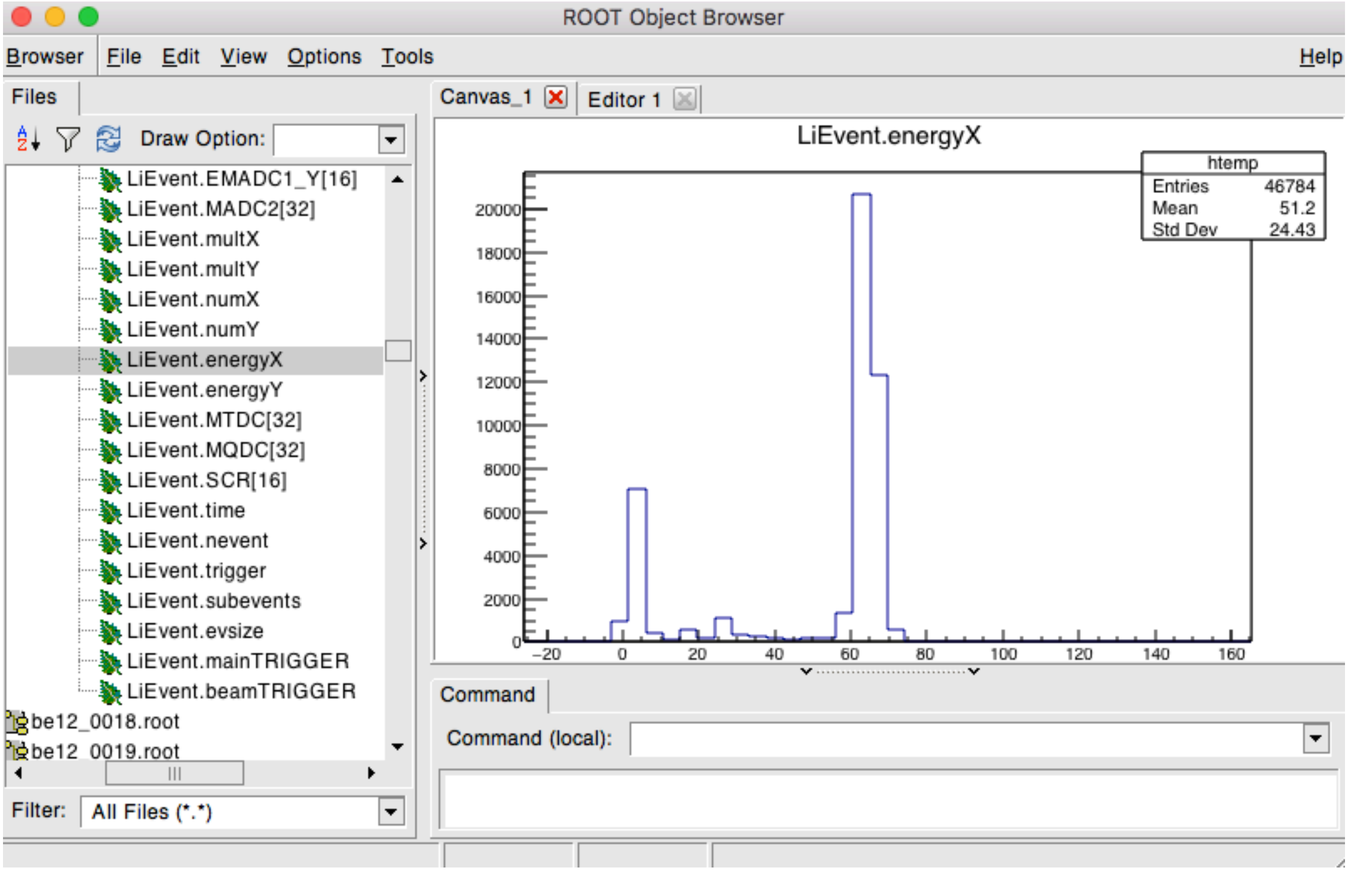

Figure 6. Example of data visualization at ROOT environment for ^{14}Be.

The first important step of the experiment was to check the ion optics configuration of the separator. Many technical settings and beam tuning has been done. The beam was tracked through the separator and its profile was checked in F3 focal plane. The profile of the ^{15}N beam at the F3 focal plane with diaphragm with d=7mm at F1 is presented in figure 7.

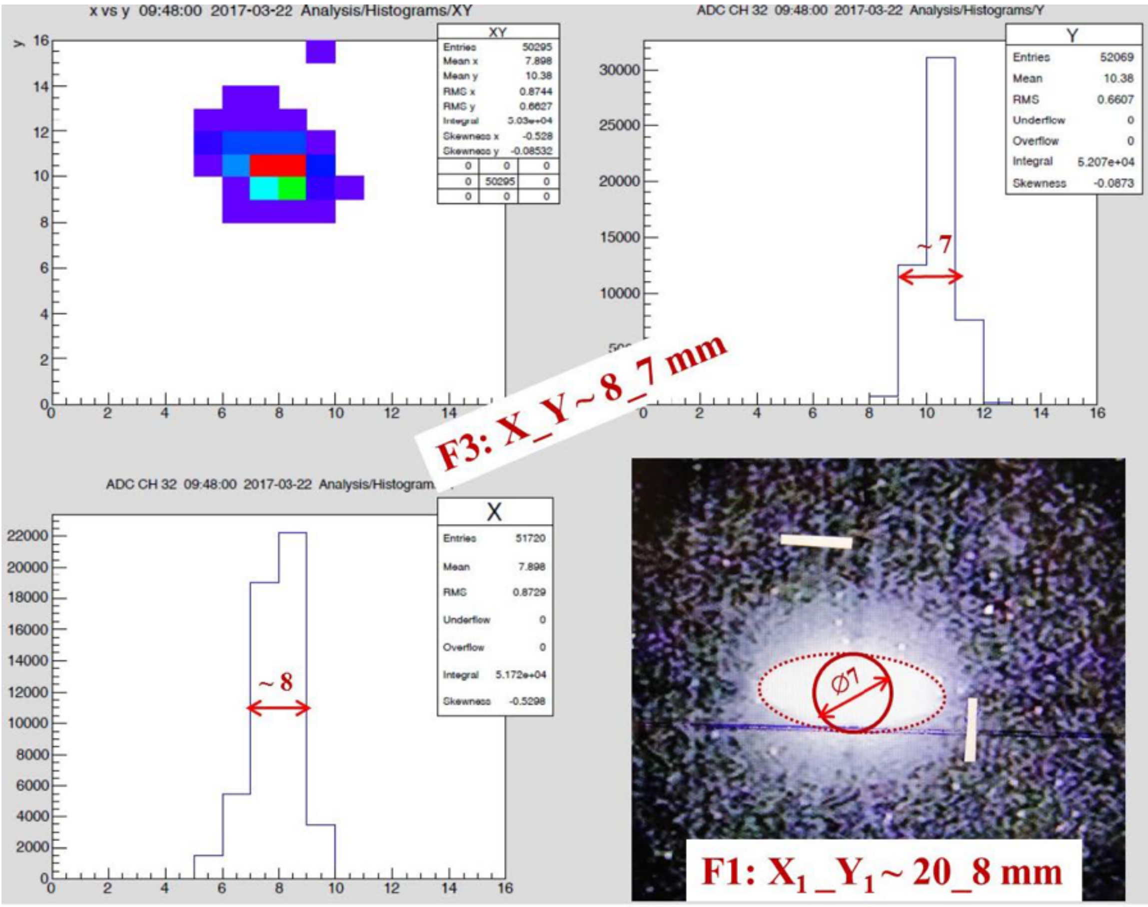

Figure 7. Profile of ^{15}N beam in F3 focal plane with diaphragm with d=7mm in F1.

For identification and selection of the radioactive one beams the time of flight (TOF) and energy loss dependence has been plotted. To receive 2-dimensional spectra dE-TOF, a script in the C programming language was created. A fragment of the example code is presented below.

genAllhist.cxx

```
#include "TFile.h"
#include "TTree.h"
#include "TH2D.h"
#include "stdio.h"
#include "Riostream.h"

void
genAllhist()
{

Double_t MTDC[32];
Double_t energyY;
Double_t energyX;
UShort_t multY;
UShort_t multX;
Double_t TOF_out;
TH2D *dE_ToF;
TFile *inF;


for (int iii=2; iii<50; iii++)
   {
   if (iii<10)
   {
   inF =new TFile(TString::Format("/Users/Ola/Documents/rootDubna/root/b8_000%d.root",
iii), "READ");
   dE_ToF = new TH2D(TString::Format("dE_ToF_%d", iii), "Si vs ToF 8B", 200, -50, 50, 200,
0, 200);
   }
   else if (iii<29)
   {
   inF =new TFile(TString::Format("/Users/Ola/Documents/rootDubna/root/b8_00%d.root",
iii), "READ");
   dE_ToF = new TH2D(TString::Format("dE_ToF_%d", iii), "Si vs ToF 8B", 200, -50, 50, 200,
0, 200);
   }
   else if (iii!=33)
   {
   inF =new TFile(TString::Format("/Users/Ola/Documents/rootDubna/root/b8_00%d.root",
iii), "READ");
   dE_ToF = new TH2D(TString::Format("dE_ToF_%d", iii), "Si vs ToF 8B", 200, 40, 180, 200,
0, 200);
   }
   TTree *inTree = (TTree*)inF->Get("AnalysisxTree");
   cout<<TString::Format("dE_ToF_%d", iii)<<endl;
   //getting desired branches
   inTree->SetMakeClass(1);
   inTree->SetBranchAddress("LiEvent.MTDC[32]", MTDC);
   inTree->SetBranchAddress("LiEvent.energyX", &energyX);
   inTree->SetBranchAddress("LiEvent.energyY", &energyY);
   inTree->SetBranchAddress("LiEvent.multY", &multY);
   inTree->SetBranchAddress("LiEvent.multX", &multX);
   bool cuts =1;
   dE_ToF->SetOption("colz");
   Long64_t nentries = inTree->GetEntries();
   for (Long64_t i=0; i<nentries; i++)
      {
      inTree->GetEntry(i);

         if (cuts)
         {
         TOF_out=(MTDC[4]+MTDC[5])/2-(MTDC[2]+MTDC[3])/2;
         dE_ToF->Fill(TOF_out, energyX);
         }
```

Figure 8. Fragment of the code written in C programming language.

The script was generating the two dimensional spectra, dE-TOF, which were used for reaction fragments identification. Example of dE-TOF spectra for the settings on ^{9}Li is presented in figure 9.

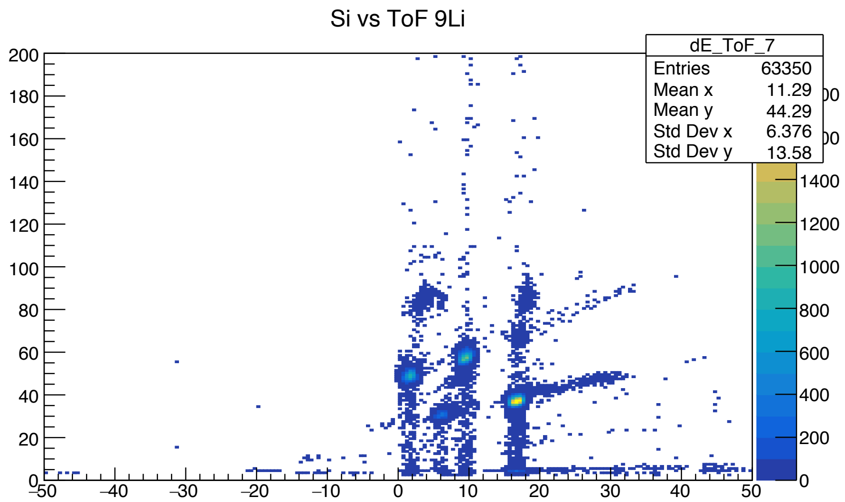

Figure 9. Example of graph presenting dE vs. TOF spectra for the settings on ^{9}Li.

With help of LISE++ software [6] it was possible to make simulations of the experimental conditions, compare and identify individual nuclei at the experimental data.

- LISE++ vs experiment

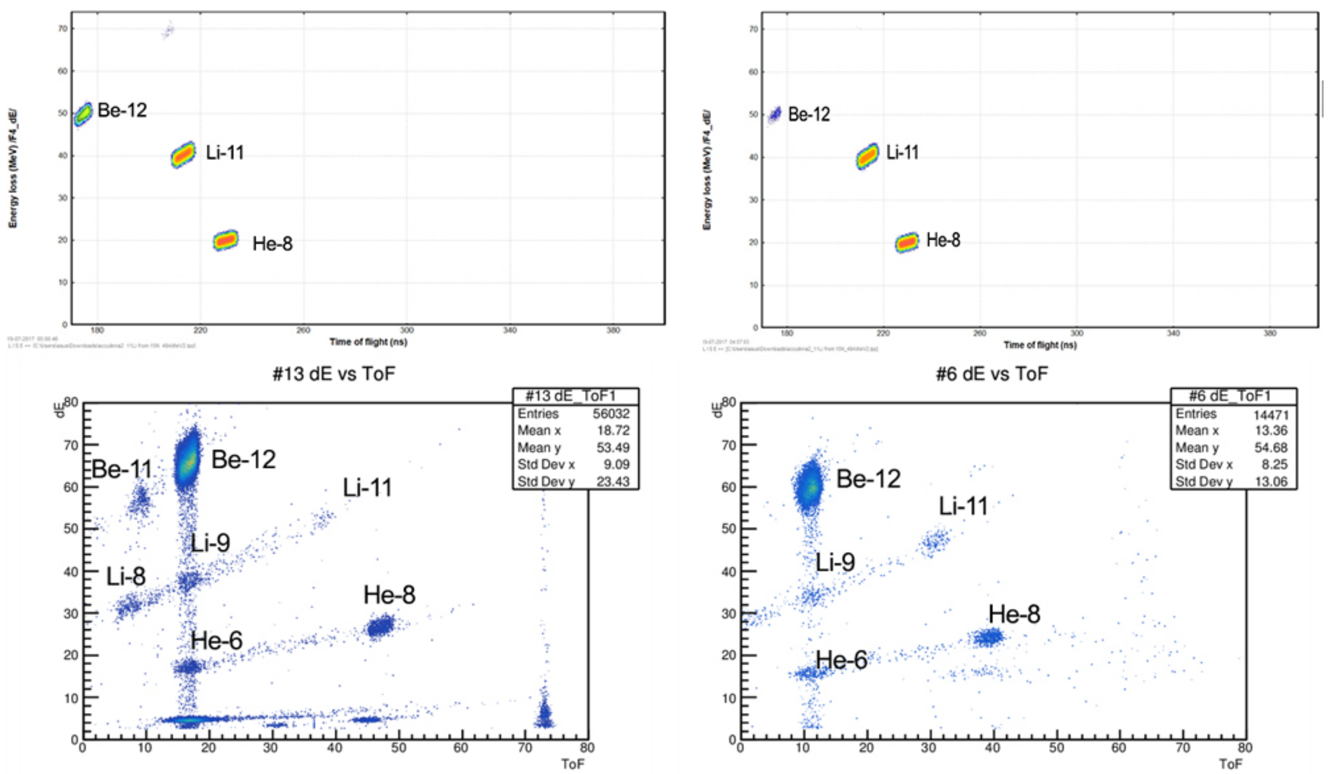

Figure 10. Comparison between LISE++ simulation and real data from experiment

In figure 10 a comparison between LISE++ simulation and experimental data is presented. As we can see, we can find similarities at the LISE++ simulated spectra and the experimental data. However, it should be noted that the axes on the upper and lower graphs are not calibrated. With this knowledge, it was possible to identify individual nuclei using simulation settings that are appropriate for the experimental settings.

- Nuclei identification

Be-12

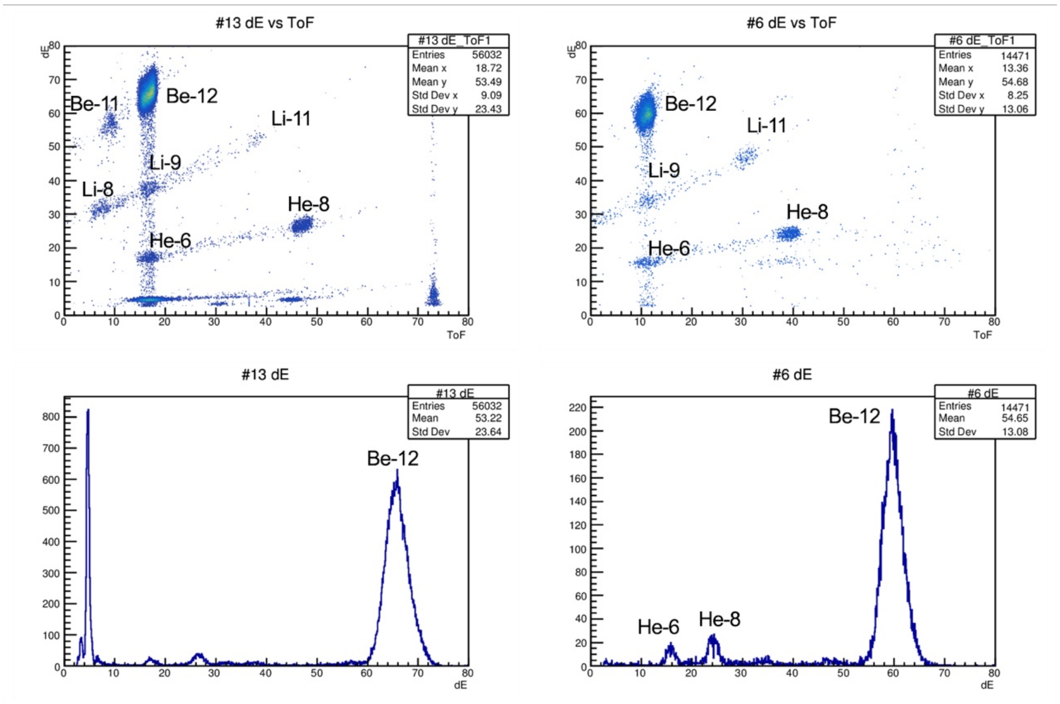

Figure 11. Nuclei identification for ^{12}Be beam in runs #13 and #6.

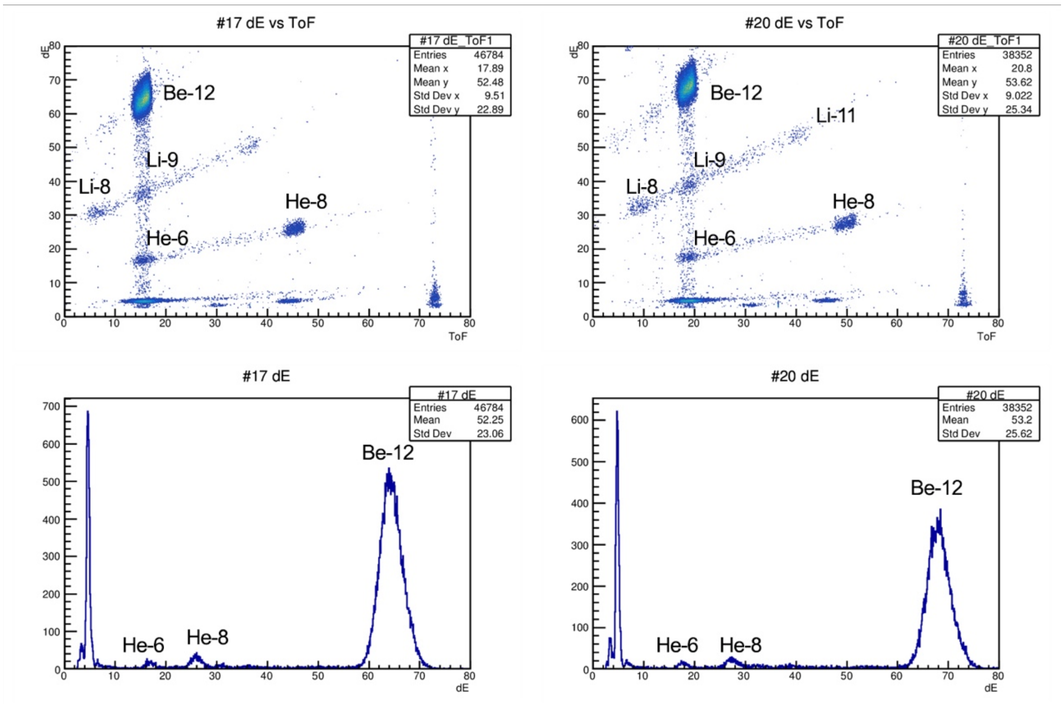

Figure 12. Nuclei identification for ^{12}Be beam in runs #17 and #20.

Li-11

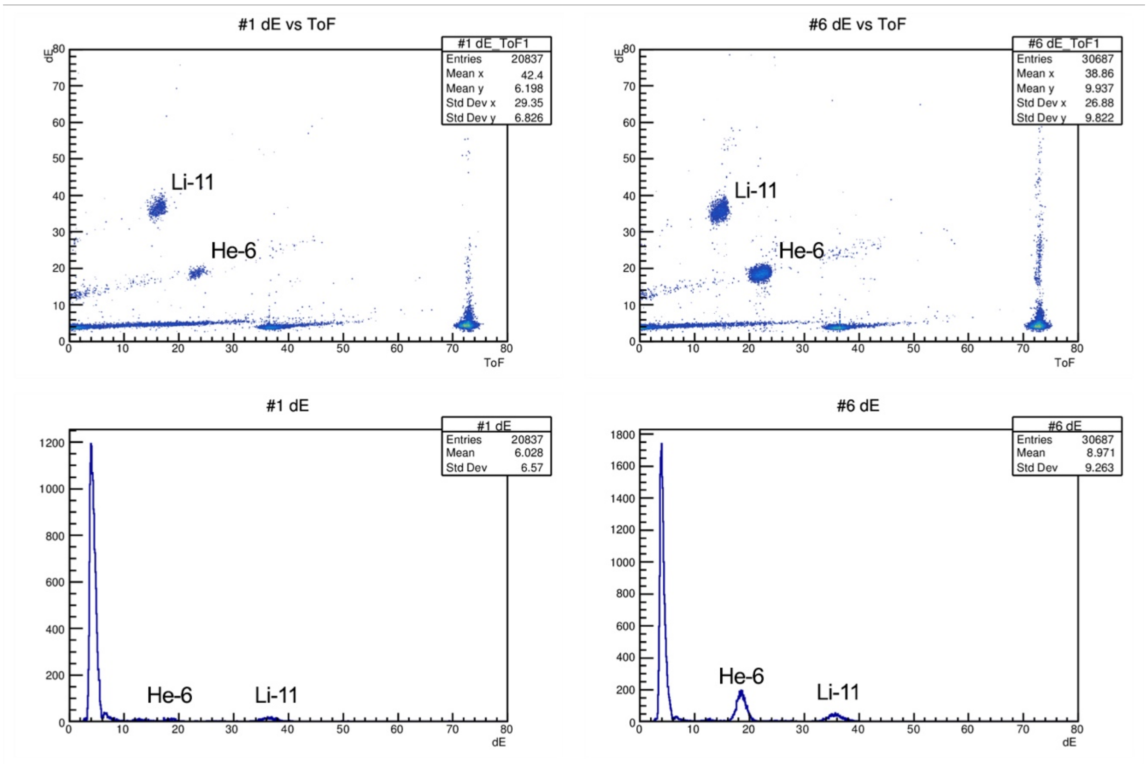

Figure 13. Nuclei identification for ^{11}Li beam in runs #1 and #6.

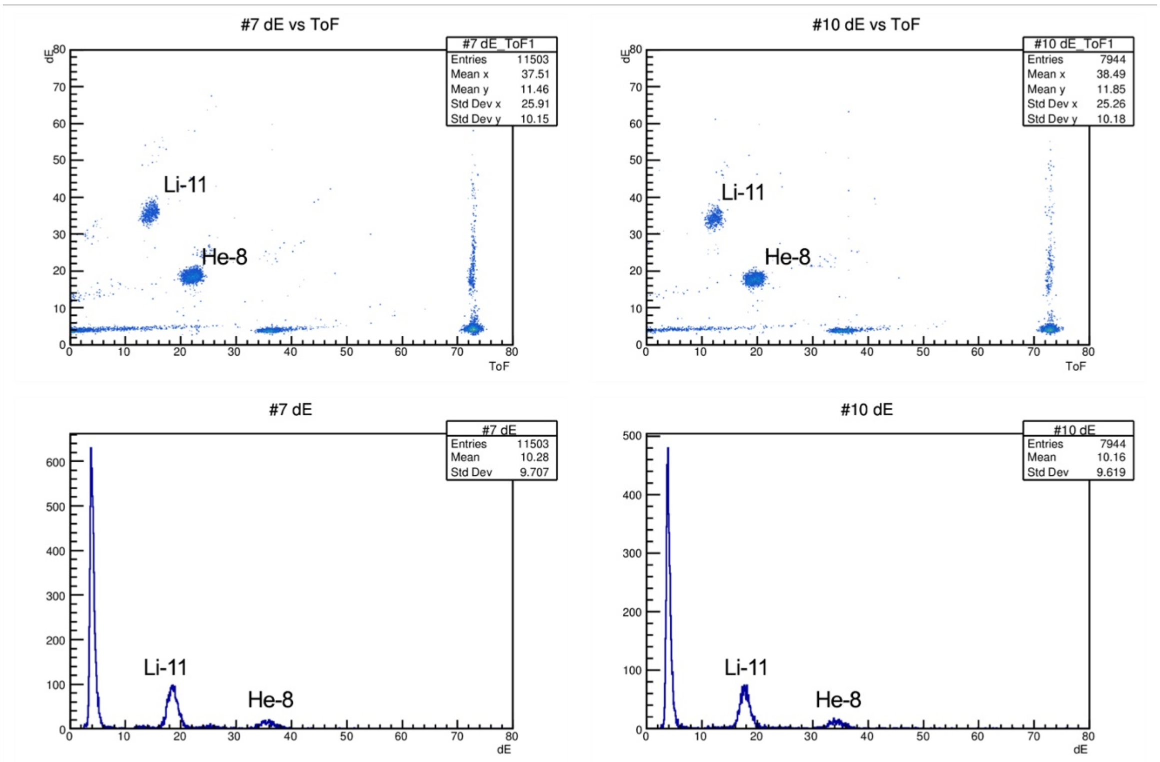

Figure 14. Nuclei identification for ^{11}Li beam in runs #7 and #10.

After analyzing the experimental data, it was possible to measure the intensity of the individual Radioactive Ion Beams. However, it is important to remember that data are preliminary.

Table 2. The measured intensity of the RIB in F5, with 1 pnA @ 7 mm ^{15}N (49.7 AMeV) + Be (2 mm); $\Delta p/p$ = 2%, $Wedge_{Be}$ = 1 mm

RIB	Energy [MeV/nucl.]	Intensity [1/s]
^{14}B	37,7	120
^{12}Be	39,4	150
^{11}Li	37,0	4
^{9}Li	33,1	1100
^{8}He	35,8	25
^{6}He	31,5	2700

Conclusions

The first experiment at the ACCULINNA-2 separator was a first successful test of the beam optics configuration of the separator. The design parameters of this facility were experimentally confirmed. The ion-optical system works according to design assumptions. Quality (purity) of beams and cross sections in F3, F4 and F5 are compatible with simulations. Multipole magnets help with additional beam focusing. The production of radioactive ion beams (RIB) in the fragmentation reaction ^{15}Ne + Be was started. The RIB intensity is on average up to 25 times higher in comparison with the ACCULINNA-1 separator. The first experimental run has been performed at the beam current 1 pnA, which is a 10^3 times less than a typical beam for the experiments delivered from the U400M cyclotron. For the production of the beams with more intensity it is necessary to install radiation shields in the cyclotron hall. The ACCULINNA-2 separator is a new basis for future studies at the FLNR in the fields of light exotic nuclei at the borders of nuclear stability.

Collected data correspond to the simulations received in LISE++. Generated graphs with dE vs E and dE vs ToF dependences has allowed to identify individual nuclei for each separator settings.

The first experimental run of the ACCULINNA-2 separator lead us to plane further, successful experiments with different types of beams and targets.

Acknowledgment

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References

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