THE FLEROV LABORATORY OF NUCLEAR REACTIONS JINR RADIOACTIVE ION BEAM PROJECT WITH THE U400M–U400 CYCLOTRON COMPLEX

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The FLNR project to produce radioactive ion beams (RIB) for nuclear physics, astrophysics and applied research with the U400M–U400 cyclotrons are presented. RIB will be produced in an ISOLDE-type target–ECR ion source assembly using light and heavy ion beams from U400M with energies up to 100 MeV/u, transported via the existing 100 m long transfer line between two accelerators and injected into the U400 cyclotron for acceleration to higher energies. The beams of exotic nuclei with Z/A ratio between 0.2 to 0.028 will be accelerated to energies of (25–0.5) MeV/u and delivered into the existing experimental areas.

1 Introduction

The future trends and progress of nuclear physics are connected with the production and applications of beams of accelerated radioactive nuclei. The radioactive ion beams (RIB) allow the production and study of nuclei in extreme states. This leads to a significant development of our understanding of the traditional fields of heavy-ion physics: synthesis of new nuclei, whose properties may differ significantly from the predicted ones, reception mechanism which may strongly be affected by the structure of the interacting nuclei, investigation of rare processes and exotic transfer reactions. RIB are also used for investigations of astrophysical aspects. They seem a promising tool for applied physics research (biophysics, biomedicine, material studies). This explains the growing interest to the methods of production of RIB, which have been the topics of a series of international conferences, symposia and workshops. Without going into details, one can say that at present at different scientific centres RIB are produced at the existing accelerators. However, great perspectives are connected with the developed and constructed new generation accelerator facilities.[1]

In FLNR investigations in heavy-ion physics are being carried out since 1960, and the accelerator basis consists of cyclotrons. With the aim to extend the possibilities of experimental investigations, in the beginning of the 80'ies a project as developed concerning a cyclotron facility including as an injector the U400 cyclotron and as post-accelerator an isochronus compact cyclotron with a 400 cm diameter (U400M). At this facility, beams of ions ranging from ^{12}C to ^{238}U with energies of 100–20 MeV/nucleon and intensities $5x10^{12}$–10^{11} s^{-1} could be obtained.[2] The new cyclotron U400M started operating in 1991. In the meantime a gallery was built for transporting the beam from one cyclotron to the other (the cyclotrons are situated in different buildings).

The analysis of the results obtained during the last years in creating different accelerator facilities with the close parameters and the substantial progress made in developing ion sources made us draw the conclusion that the cyclotron U400M combined with a modern ECR-source can substitute the suggested cyclotron complex.

At the same time, these two available big cyclotrons are a good basis for the creation a modern ISOLDE-type RIB facility, where U400M will be the production stage and the U400 will be the postaccelerator one.

2. General description of the U400M–U400 cyclotron complex for RIB

2.1 U400M cyclotron

The compact type isochronus cyclotron with the pole diameter 400 cm (U400M) and k = 400–540, commissioned in 1991, is intended for acceleration of light and heavy ion beams with Z/A ratio of 0.5–0.1 at energies ranging from 100 to 6 MeV/u. At the beginning of 1995 a new axial injection system with ECR ion source operating at 14 GHz (DECRIS–14), which was elaborated at FLNR, has been built and tested. At the present time experiments by means of primary beams are being done using new physics set up such as the 4π–detector array of charged particles and nuclei FOBOS and high resolution large acceptance projectile-like fragment separator COMBAS. The main programme of the investigation planned at U400M is that are involving the studies with RIB. For its realisation a new high resolution beam line (HRBL) has built.[3]

In Fig.1 the layout of the projected is shown. The first quadrupole doublet working in accord with the preceding magnet provides the focus of primary beam on the main object slit of the size of 3 x 5 mm^2, correspondingly, in horizontal and vertical directions. The HRBL by itself involves 30° sector dipole magnets and four doublets of quadrupoles. This line will transfer RIB to the physics target positioned in the focal plane of the beam line. Maximum momentum rigidity of the beam line will be 3.8 Tm. A RIB production target will be placed in the position in the main object slit when RIB are transferred to the physics target. This production target will be either of solid rotating materials or a gaseous state target. Gaseous hydrogen at a pressure of about 30 bar will be one of the most favourable targets allowing to obtain neutron rich RIB in inverse kinematics proton knock-out reactions.

The HRBL is refereed as taking together the beam line discussed above and the QD spectrometer following this line. It involves a quadrupole and a wide-aperture 60° dipole magnet. Reaction products emerging from the target within a solid angle of a 2.8 msr and having a momentum spread of ±12% will be collected in the spectrometer focal plane with the momentum resolution 2×10^{-4} for a 1 mm target width.

Operation modes of the whole set up will be distinguished by two different tunes of the beam line. In the so-called achromatic mode it will have an intermediate focus in its symmetry plane where a special profile degrader will be installed for elimination of impurities in the produced RIB. Exotic nuclei emerging from the production target within a solid angle of a 0.28 msr and having a momentum spread of ±0.5% will be transmitted to the physics target with about one-to-one main object magnification if the degrader profile is chosen to preserve the achromatic image. Another degrader profile, monokinetic one, is possible allowing to reduce the RIB momentum spread down to 3×10^{-3} at the expense of the increase of the RIB losses. The same momentum resolution will be obtained in the QD spectrometer focal plane for the products of RIB reactions occurring on the physics target.

The estimates of possible fluxes which could be obtained on the physics target of the discussed set up for some RIB being of interest were made. Results of these estimates obtained for 50 MeV/u primary beam of the intensity of 1 pμA are presented in Table 1 for the production target of hydrogen with thickness 10^{22} cm^{-2}.

Table 1

RIB	RIB energy (MeV/u)	Reaction	Flux (s^{-1})
^{6}He	49	^{7}Li+ ^{1}H	1.5×10^{7}
^{8}He	49	^{11}B+ ^{1}H	9×10^{3}
^{8}B	48	^{10}B+ ^{1}H	1.3×10^{6}
^{9}Li	49	^{11}B+ ^{1}H	1.8×10^{6}
^{11}Li	49	^{18}O+ ^{1}H	1.5×10^{2}
^{12}Be	49	^{18}O+ ^{1}H	1.2×10^{3}
^{14}Be	49	^{18}O+ ^{1}H	4.4×10^{1}
^{16}C	48	^{18}O+ ^{1}H	8.7×10^{6}

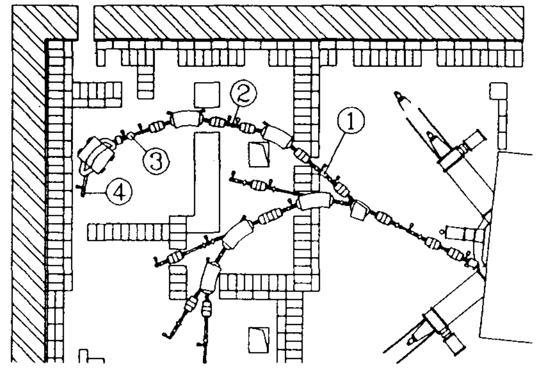

Figure 1: HRBL layout. 1–RIB production target; 2–degrader position; 3–main physics target; 4–QD spectrometer focal plane.

In the case of the RIB complex for activity production such ions as Li, C, N, O, Ne with energies of (60–80 MeV/u) and intensities of 10^{13} s^{-1} will be used. Except heavy ions U400M cyclotron is able to accelerate beams of protons ($^{2}H^{1+}$) and ^{3}He ($^{3}He^{1+}$) with the energies of 100 and 150 MeV respectively, which beams can be extracted by means of stripping method with the efficiency of ~100% and high intensity (up to 10^{14} s^{-1}). In comparison with heavy ions these ion beams will allow for certain numbers of isotopes to get high enough yield and, consequently, higher RIB intensities.

2.2 Production and transport of RIB

The primary light and heavy ion beams accelerated by the U400M cyclotron will bombard a production target located in the well-shielded area in the machine vault. The radioactive atoms produced by nuclear reactions will be released from the target which will be at the high temperature (~2300 K) and will pass through a transfer tube into an ECR ion source. The radioactive ions will then be ionised up to charged state corresponding to the ratio Z/A from 0.028 to 0.2. After extraction from the ECR, the low energy RIB (acceleration voltage around 20 kV) will be selected by a relatively low resolution separator ($\Delta A/A = 3 \times 10^{-3}$), transported via existing 100 m long transfer line between U400M and U400 accelerators and injected into the U400 cyclotron for acceleration to high energies.

For activity production in most cases carbon target will be used due to its excellent release properties, low atomic number and high sublimation temperature. For the next two years we are planning to create on U400M a special beam channel in order to study systematically different versions of the target set up and target materials and transport of radio nuclei by making use of both the existing and new methods.

The 10 GHz ECR ion source (DECRIS–10) developed in FLNR is planned for the use at the RIB production (Fig. 2).

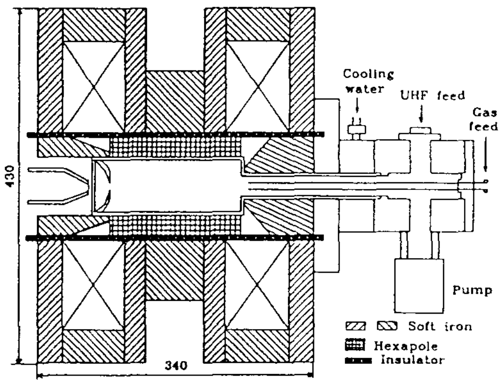

Figure 2: Cross section of the DECRIS–10.

The new idea of this source is that it will be equipped with multipolar permanent magnet with continuous easy axis orientation, in this case the thickness of the multipolar magnet can be decreased greatly and more space can be left for the magnetic coils, which result in low consumption of permanent magnet material, higher axial magnetic field, lower electric power consumption and relatively low price. Particular emphasis has been put on the optimized studies of the magnetic fields configuration. Two different field shapes for middle and higher charge states with high ion currents were designed. An intensive axial magnetic field up to 1.2 T for both cases is got by fine optimization, while the electric power consumption for magnetic coils is less than 40 kW.

The beam focusing along the transfer line will be made either with solenoids or quadrupole lenses, and for aberration correction sextupole magnet will be used.

One of the serious problem arising at the transport such a low energy beam between the cyclotrons is the problem of the high vacuum in the beam line. In fact, the low energy ions of high charge states have a high enough electron capture cross section which one can obtained from the formula describing well the experimental results.[4]

$$\sigma_{z,z-1} = 1.43 \times 10^{12} \times Z^{1.7} \times R^{-2.76}$$

where $\sigma_{z,z-1}(cm^2)$ is the electron capture cross section, Z (Coulomb) is the ion charge, R (eV) is the first ion potential of the target (residual gas N_2).

The calculated transmission factors for some RIB are shown in Fig. 3 as function of the gas pressure in the beam line.

Adequate pumping speed is provided by six cryogenic pumps (1000 l/s per pump). Operating pressure lies around 10^{-8} mbar which keeps the beam loss rate for the heaviest ions bellow 6%. In order to get such a pressure certain condition of vacuum hygiene should be kept (preliminary treating and cleaning of vacuum surfaces, utilization of the metallic seals, etc.)

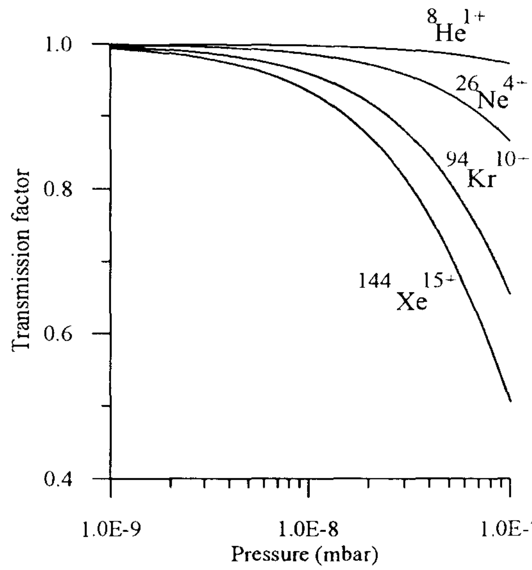

Figure 3: The transmission factor for some RIB.

2.3 U400 cyclotron

The compact type isochronus cyclotron U400 with pole diameter 400 cm and k = 625 being in operation since 1980 is intended for the delivering of intense beams of heavy ions having the ratio Z/A = 0.2–0.08 and accelerated at the 2nd harmonic to the energy of (25–5) MeV/u and the ions with the ratio of Z/A = 0.06–0.028, accelerated at the 6th harmonic to the energy of (2.7–0.5) MeV/u. At this cyclotron a three-level multiposition beam transport system is created, which involves 12 beam lines where different physics set up are installed such as the gas filled and electrostatic separators used for the study and synthesis of superheavy elements. At present the beam axial injection is being created at this cyclotron based on the ECR–4M (at 14 GHz source built at GANIL). The injection system involves a spiral inflector and is similar to already built at the U400M cyclotron. A more detailed description of the system is given in another paper presented at this conference.

As it was mentioned, RIB are injected into the central region of the cyclotron after the passage of the transport gallery and are accelerated to the same energy as the stable beams which are accelerated at present time. Separation of the isobars will be accomplished by the cyclotron itself – which is a good spectrometer for fast ions.[5] For the case of the U400 internal beam the resolving power will be $\Delta A / A \leq 2.8 \times 10^{-4}$. Additionally separation can be obtained for the beam extracted from the cyclotron by making use the stripping method. Experiments on the separation of the $^{48}Ti^{6+}$ and $^{56}Fe^{7+}$ ions, extracted by these methods shown that the resolving power of the cyclotron makes 1.9 x 10^{-4}. As for predicted RIB intensities for this complex one can anticipate at present the intensity of 5 x 10^9 s^{-1} for the beams of noble gases.

We note that except RIB being the exotic beams there is whole set of ions of rare isotopes also possessing the exotic, as ^{26}Mg, $^{34,36}S$, ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni, ^{70}Zn, ^{76}Ge. These ions are being accelerated at present at U400 cyclotron to the energy of (5–7 MeV/u) and intensity of 10^{12}–10^{13} s^{-1} by making use of the internal PIG source. According to our estimate, ECR–4M ion source will allow to obtain approximately the same intensities however in a more broad energy range at a considerably lower material consumption. As compared to RIB, the intensity of such beams will be higher by several orders of magnitude, and this might be the certain advantage for some kind of physics investigations.

It is recognized well that for increasing the beam intensity simultaneously with a considerable improvement of its quality, the most optimal solution is the use of storage ring with electron cooling. Therefore, one of the versions of the future development of this facility might be the creation of a storage ring (just a cooler, without any acceleration) with B_ρ = 2 Tm. This would enable us to obtain high precision RIB with the emmitance of < 1π mm mrad and momentum spread of < 10^{-5}. The layout of the RIB facility is presented in Fig. 4.

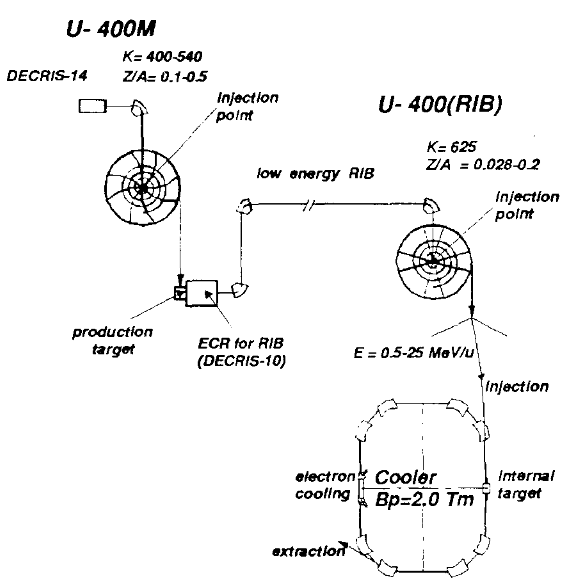

Figure 4: The conceptual view of U400M–U400 facility.

3 Conclusion

The work on the creation on the cyclotron complex U400M –U400 is the part of the FLNR programme of the development of accelerator and experimental facilities for carrying out nuclear physics investigations by means of primary and secondary beams. This approach defines, to a large degree, the project time schedule which now appears to us as follows:

1. Creation of the target set up on the U400M cyclotron — **1996**
2. Study of the radioactive nuclear transport from the target to the ECR ion source — **1997**
3. Creation of the ECR ion source (10 GHz) and the ISOL separators — **1997–1998**
4. Creation of the low energy RIB transport line from the ECR ion source to the U400 cyclotron — **1998–1999**
5. Acceleration of the RIB on the U400 cyclotron — **1999–2000**

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