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HIGH RESOLUTION BEAM LINE OF THE U400M CYCLOTRON AND RIB ACCUMULATION AND COOLING IN THE K4 STORAGE RING

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Канал пучка высокого разрешения на циклотроне У-400М
и возможное накопление радиоактивного пучка в кольце К4

Описан канал пучка высокого разрешения АКУЛИНА с точки зрения его применения как составной части проекта TREBLE [1]. Возможности получения радиоактивных пучков на этом канале продемонстрированы в экспериментах по фрагментации первичного пучка ^{14}N с энергией 51 МэВ·А на графитовой мишени толщиной 170 мг/см^2. Представлены характеристики полученных радиоактивных пучков ^6He, ^8He и ^8B. Предложена схема накопления и охлаждения на орбите кольца К4 радиоактивного пучка низкой интенсивности, полученного на данном канале.

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High Resolution Beam Line of the U400M Cyclotron
and RIB Accumulation and Cooling in the K4 Storage Ring

The high resolution beam line ACCULINNA put into operation on a primary beam line of the JINR U400M cyclotron is discussed in the framework of the TREBLE project [1]. The capability of the beam line for producing radioactive ion beams is demonstrated by means of nuclear fragmentation of the primary ^{14}N beam, with the energy of 51 MeV·A, on the 170 mg/cm^2 carbon target. Characteristics of the obtained ^6He, ^8He and ^8B radioactive beams are presented. A scheme of accumulation and cooling on the orbit of the storage ring K4 is proposed for a low intensity radioactive beam obtained from this beam line.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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1. INTRODUCTION

The Dubna project of two coupled storage rings K4-K10 intended to provide cooled beams of short lived exotic nuclei had been developed in 1992 [2-4]. The principal concept of the project was as follow. A primary heavy ion beam from the JINR cyclotron U400M is accumulated and cooled in the first ring K4 and then its energy is increased up to about 120-170 MeV·A. The cooled primary beam fast extracted from the ring K4 is used to produce an exotic beam which, after separation by an energy loss achromat, is injected into the second ring K10. It was shown that the nuclei with the lifetime more than 1 s can be cooled and accumulated on the K10 ring orbit. For the shorter lived nuclei, a target irradiation is preferable just after cooling. The cooling time in the second ring is of the order of 50 ms which results from a low initial phase space of the secondary beam generated on the production target. The transverse emittance is small since the secondary beam is produced after focusing the high quality primary beam onto a very small target spot of less than 1 mm in diameter. The same is also true for the longitudinal emittance due to the possibility to extract from the first ring the primary beam in the form of very short (~20 ns) bunches.

According to estimations the realisation of this project would provide the energy-controlled good quality beams of radioactive ions with the luminosity, on a thin internal target, ranging from 10^{23} to 10^{28} $s^{-1}\cdot cm^{-2}$ for very short lived nuclei, such as (in the order of the luminosity increase) ^{18}C, ^{28}Ne, ^{11}Li, ^{22}O, ^{16}C, ^{6}He, ^{9}Li and ^{12}B, and from 10^{27} to 10^{30} $s^{-1}\cdot cm^{-2}$ for more long lived ones as ^{11}Be, ^{14}O, ^{24}Ne, ^{28}Mg, ^{38}S and ^{44m}Sc.

In 1993 the first stage of the project realisation (TREBLe) was proposed [1]. A secondary beam emerging from the target, is captured by a separation channel and injected immediately into the ring K4. In this case it is anticipated that the luminosities on the K4 ring orbit to be less by a factor of 10^3 as compared with the ones of the full scale project. In the framework of this reduced project a separation channel, called from here on as the beam line ACCULINNA, was put into operation in 1996.

The ACCULINNA design parameters allow to obtain on gaseous (H_2) or metallic (Be) production targets, purify and deliver to a physics target beams of ^{6}He, ^{8}He, ^{8}B, ^{9}Li, ^{9}C, etc. of the intensity of 10^4-10^7 s^{-1} [5]. In the near future systematic investigations of the lightest of the above mentioned nuclei, namely ^{6}He, will be performed. The ^{6}He beam will be generated via the reaction $^{7}Li + {}^{1}H \Rightarrow {}^{6}He + 2p$. The beam of ^{7}Li ions, in the charge state of 2^+ accelerated, by the cyclotron to the energy of 44 MeV·A will be used as the primary beam. In this case one can get a quite pure ^{6}He radioactive nuclear beam with the energy of about 40 MeV·A and the intensity of the order of 10^7 s^{-1}.

2. FACILITY LAYOUT

The layout of the beam line ACCULINNA is shown in Fig.1. To produce RIB's a magnetic quadrupole doublet Q01-Q02 focuses the primary beam, delivered from the cyclotron, onto the main object slit F_1 where the production target is placed. The design dimensions of the main object slit are 3×5 mm^2, respectively in horizontal and vertical directions. The radioactive beams created are transported towards a physics target F_3 where nuclear physics experiments take place. The ACCULINNA beam line itself includes two magnetic dipoles (D1,D2), eight magnetic quadrupoles (Q1-Q8) and two magnetic sextupoles (SX1,SX2). The facility has a mirror symmetry against the transverse intermediate plane F_2. There are two operational modes of the differed in optical conditions in the physics target plane F_3 and, as a consequence, in the intermediate plane F_2. The main ion-optical parameters of the modes, being called from here on as achromatic and dispersion ones respectively, are given in Table 1.

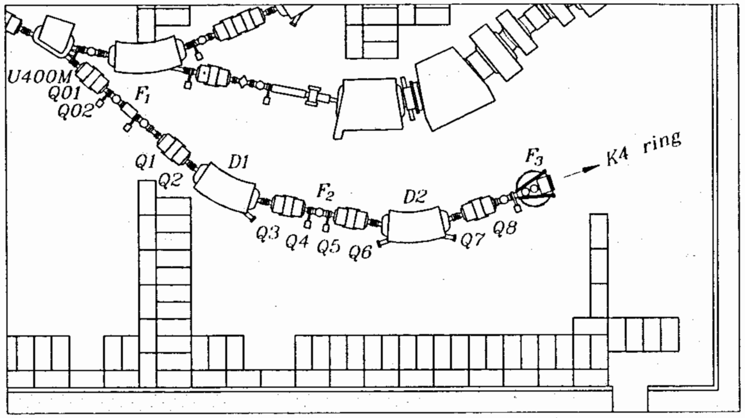

Figure 1. The ACCULINNA beam line.

In the first mode there are a dispersionless fully achromatic focus of the beam on the physics target and a moderate momentum resolution in the plane F_2. The latter plane is an appropriate place for installing wedge degraders to purify the beam of interest. Depending on the wedges, achromatic or monoenergetic ones [6,7], the beam line optics after the degrader will be either the same as it would be without any degrader, e.g. the beam will have the above mentioned achromatic focus on the physics target, or the energy spread of the beam will be decreased to some extent at the expense of increasing the transverse phase space of the beam.

The dispersion operational mode, mainly foreseen for working with primary cyclotron beams, provides a possibility to have on the physics target a rather good momentum resolution. In this case, in conjunction with a following spectrometer, conditions which are inherent in the so called momentum loss spectrometer can be reached.

For rotation of either the intermediate focal plane in the achromatic mode or the physics target focal plane in the dispersion mode, two magnetic sextupole lenses SX1 and SX2 are provided. These sextupoles are housed in the drift spaces between the lenses Q3 and Q4 and the lenses Q7 and Q8, respectively.

The ion-optical characteristics of the beam line ACCULINNA up to the second order were calculated via the TRANSPORT program [8].

3. TEST EXPERIMENTS

Two test experiments were carried out in the first half of 1996. The cyclotron beam of $^{14}N^{7+}$ with the energy of about 51 MeV·A was used for defining the main ion-optical

Table 1.
The ACCULINNA beam line characteristics.

Operational mode		achromatic in F_3	with dispersion in F_3
$B\rho_{max}$	[Tm]	3.6	3.4
Solid angle	[msr]	0.3	0.5
Horizontal acceptance angle	[mrad]	±9	±10
Vertical acceptance angle	[mrad]	±8	±20
Momentum acceptance	[%]	6	0.8
Intermediate focal plane F_2:			
Horizontal magnification	-	0.43	-
Vertical magnification	-	2.0	-
Momentum dispersion	[cm/%]	0.56	-
Momentum resolution (FWHM)[a)]	-	$1\cdot10^{-3}$	-
Focal plane F_3:			
Horizontal magnification	-	1.0	1.67
Vertical magnification	-	1.0	1.0
Momentum dispersion	[cm/%]	0	4.91
Momentum resolution (FWHM)[a)]	-	none	$3\cdot10^{-4}$
Full length of the beam line	[m]	12.594	12.594

[a)]Main object slit width = 1mm. Second-order aberrations are taken into account.

characteristics of ACCULINNA tuned to the achromatic mode. The carbon collimator with a slit of the size of 3×10 mm^2 was installed in the main object position F_1 of the beam line.

To measure the transmission of the beam, four Faraday cups were applied. The first Faraday cup was installed just after the beam exit from the cyclotron. The other three measured the beam intensity, respectively, after the main object slit, in the intermediate focal plane F_2 and in the achromatic focus F_3. As the experiments showed, about 70% of the ^{14}N beam coming from the U400M cyclotron can be rather easily focused onto the main object slit mentioned above. From the whole beam that passed through the slit about 90% of ions were transported up to the achromatic focus plane.

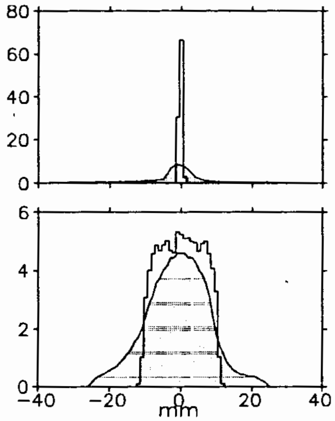

Figure 2. The horizontal (top) and vertical (bottom) ^{14}N beam profiles (histograms - calculated, smooth curves - measured) in the intermediate focal plane F_2. The measured FWHM are 7 and 20 mm, respectively. The calculated profiles are simulated for the monochromatic beam. The main object slit is equal to 3×10 mm^2.

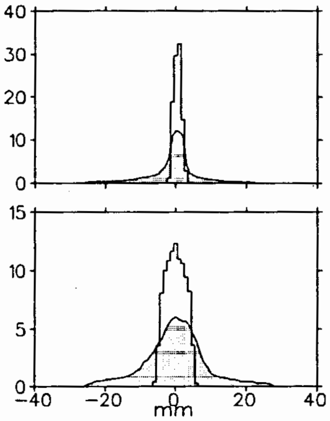

Figure 3. The same profiles as in Fig. 2 but in the achromatic focal plane F_3. The measured FWHM widths are 5 and 12 mm, respectively. The calculated profiles are simulated for beam momentum spread of 1.3%. The object slit is as in Fig. 2.

Other measurements were made to observe the momentum resolution in the intermediate focal plane F_2 and the sizes of the images of the object slit in the planes F_2 and F_3. For this purpose two multiwire proportional chambers installed in these planes were used. Both, the measured and calculated beam profiles are shown in Fig.2 and Fig.3. The calculations were done under assumption of the isotropical and homogeneous distribution of the beam emerging from the object slit. The profiles are in a reasonable accord to each other. A factor of 1.7 of the achromatic plane F_3 image broadening of the 3 mm object slit is determined by the second order aberrations arising in the system after excitation of the sextupole SX1 to correct the momentum resolution in the intermediate focal plane F_2. However we were not able to reach the calculated momentum resolution in the plane F_2 (see Table 1). The reason seems to be due to a rather broad energy spread of the cyclotron beam. This spread as well as the transverse emittance of the beam was not being controlled during the experiments. Going from the measured FWHM profile of 7 mm the energy spread can be estimated as being about 2.5%. Taking this energy spread into account we believe that the beam profile obtained in the focal plane F_3 is similar to that what one should have also for RIB's.

Finally, a series of experiments dealing with the producing of radioactive ion beams at fragmentation of 51 MeV·A $^{14}N^{7+}$ cyclotron beam on carbon was performed. A carbon production target of the thickness of 170 mg/cm^2 was installed in the object slit position F_1. A momentum selection slit diaphragm of the size of 22×20 mm^2 was applied in the intermediate focal plane F_2. It restricted the RIB momentum spread to the value of about ±2%. The

diaphragm construction allowed for the mounting of wedge degraders. An achromatic aluminium wedge was used in these experiments. Its thickness, taking along the optical axis of the beam line, was 210 mg/cm^2. Radioactive beams were observed and identified by a detector telescope consisting of a 300μ Si ΔE-detector and a CsI(Tl) E-detector with the cross section of 20×20 mm^2 and the thickness of 15 mm. The telescope was installed in the achromatic focal plane F_3. There was not any diaphragm in this plane, and all ions entering the ΔE-E detectors system were registered.

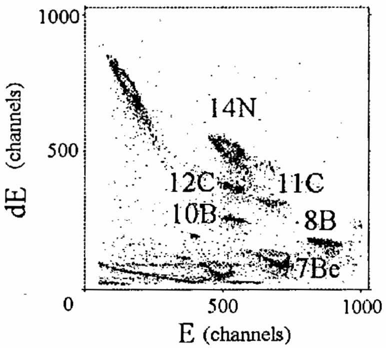

Figure 4. ΔE-E beam matrix for the beam line tuned to the optimal yield of ^8B ions.

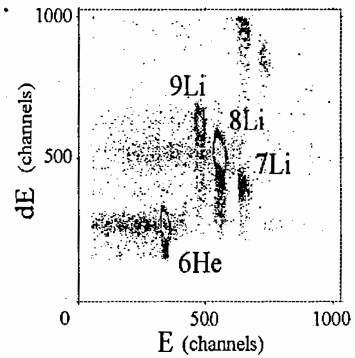

Figure 5. ΔE-E beam matrix for the beam tuned to optimal yield of ^6He ions

In Fig.4 and Fig.5 are given beam matrices obtained when ACCULINNA was tuned to optimal production of $^8B^{5+}$ and $^6He^{2+}$ ions, respectively. The corresponding yields normalised to the ^{14}N beam current of 70 pnA are presented in Table 2. To calculate the yields, the GANIL program LISE was used. The ^{14}N current given above is a routine one to reach by the cyclotron U400M at present. In reality, due to the high intensity of the radioactive ions on the detectors, all experiments were carried out with the ^{14}N current of one tenth as high. For the same reasons we did not present data for ^8B produced without the wedge degrader. A considerable discrepancy between the predicted and experimental values of the ^8B yield seems to come from a corresponding overestimation of the reaction cross section used by the program.

The result obtained is of promise for us. The matrices will obviously be considerably purified without a noticeable decrease of the intensity of the radioactive beam of interest if we use a horizontal slit of about 5 mm in front of the detectors. As to the intensities, a gain of a factor of 10 will be reachable due to simple increasing of the intensity of the primary beam. At present this intensity is restricted by the radiation problems. Therefore, using even this badly non-optimal reaction to produce ^6He beam, this ions with the intensity of about some factor of 10^4 pps can be obtained.

Table 2
Yields (pps) of various RIB's in the reaction $^{14}N^{7+}$ (51 MeV·A, 70 pnA) + carbon (170 mg/cm^2). Wedge thickness is 210 mg/cm^2 of aluminium.

	Tuning to ^8B		Tuning to ^6He	
	Present data	Calculation	Present data	Calculation
^{12}N	5	-	-	-
^{11}C	52	-	-	-
^{10}C	2	-	-	-
^9C	5	160	-	-
^{10}B	63	-	-	-
^8B	2.5×10^2	3.5×10^3	-	-
^{10}Be	-	-	10	38
^7Be	3.1×10^3	7.1×10^3	-	-
^9Li	-	-	240	120
^8Li	-	-	1.0×10^3	3.2×10^3
^7Li	26	-	78	120
^6Li	9.1×10^3	2.0×10^3	-	-
^6He	-	-	1.3×10^3	6.0×10^3
^4He	1.8×10^3	-	-	0.02

4. RIB STORAGE IN THE RING K4

The factors that strongly influence in the accumulation and electron cooling of radioactive beams on the orbit of the ring K4 are the momentum spread of the injected beam and its transverse emittances. On the one hand, they are to be as much as possible to get the high intensity of the beam injected and, on the other hand, with increasing the beam phase space the electron cooling time augments. As to the transverse emittance, it is fixed at the value of 15π mm·mrad resulting in the transverse cooling time of about 50 ms for such ions as, e.g. $^8B^{5+}$ $^{17}N^{7+}$, $^{14}O^{8+}$ and $^{20}O^{8+}$ having the energy of 40-50 MeV·A. In terms of the longitudinal emittance, to widen the accessible momentum of the beam accumulated in the ring beam debunching [1] was proposed before the injection in the K4 ring. This would reduce by a factor of ten the initial momentum spread (±1%) of the secondary beam. As a consequence, the longitudinal cooling time being comparable with the transverse one mentioned above seems to be reachable.

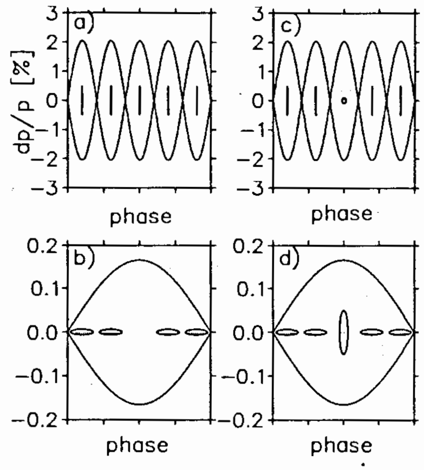

Figure 6. Possible scheme of storing and accumulation of quasicontinuous beam of radioactive ions in the ring K4: a) the first step of injection and capture into the 19th harmonic RF buckets (only 5 buckets are shown); b) the situation after the 1/4 synchrotron rotation of the 1 ns bunches and switching on the first harmonic RF cavity with the amplitude of 100V; c) one of later events of the single turn injection with some ions stored in the 0° phase separatrix; d) the last but one act of injection with storing of ~5×10^4 ions in the bunch with duration of about 5 ns.

In connection with finding a compromise between the longitudinal cooling time and the momentum spread of the beam injected it would be worth to consider another injection scenario that seems to hold in case of storing radioactive beams. The idea is to make use of the fact the beam injected has longitudinal structure consisting of 1 ns microbunches that follow one after another in 50 ns. Therefore, keeping in mind that the revolution period in the ring is about 1 μs one can carry out the single turn injection of radioactive ion beam when the ring RF cavity, phase synchronised with the cyclotron cycle, is tuned, say, to the 19th harmonic, and execute the 1/4 synchrotron rotation of the injected beam bunches. If the radioactive beam momentum spread after the ACCULINNA beam line is ±0.5%, then for catching the microbunch into a RF bucket (Fig.6a) the RF amplitude should be about 300 kV which is twice as large as the minimum RF amplitude in these conditions. Just after the 1/4 synchrotron rotation the 19th harmonic RF cavity is switched off leaving the beam momentum spread decreased by at least 50 times (Fig.6b). This will provide the longitudinal cooling time of the order of 20 ms. Next step is to switch on another properly phase synchronized cavity tuned to the first harmonic with the RF amplitude of about 100V. This amplitude fits well the small beam momentum spread existing at this moment (Fig.6b). After this, the electron cooling will result in the longitudinal merging of all 19 microbunches and in the formation of a single bunch with the duration of less than 5 ns. This bunch length will be obtained if the number of stored ions does not exceed $5\cdot10^4$ [2]. Then, one switches off the first RF harmonic and turns on the 19th harmonic number cavity. After this point, one can make another single turn injection (Fig.6c,d). The limitation on the maximum intensity of so accumulated radioactive beams comes from the necessity to keep, during the 1/4 synchrotron bunch rotation, the momentum spread of the previously cooled beam at the value ≤0.1%. The process described is a modification of the multiple single turn injection proposed for the K4-K10 project [2-4].

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