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HIGH RESOLUTION LINE FOR SECONDARY RADIOACTIVE BEAMS AT THE U400M CYCLOTRON

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Канал высокого разрешения для радиоактивных пучков на циклотроне У-400М

Для выполнения программы экспериментов по изучению ядерных реакций с радиоактивными пучками в энергетическом диапазоне от 20 до 80 МэВ·А на циклотроне У-400М сооружен и испытан канал пучка высокого разрешения АКУЛИНА. С применением реакции фрагментации первичного пучка ^{14}N с энергией 51 МэВ·А на графитовой мишени толщиной 170 мг/см^2 получены радиоактивные пучки ^6He, ^8He, ^8B. Обсуждаются пути дальнейшего развития установки.

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High Resolution Line for Secondary Radioactive Beams at the U400M Cyclotron

For implementation of an experimental program for studying nuclear reactions with radioactive ion beams in the energy domain of 20 through 80 MeV·A the high resolution beam line ACCULINNA was put into commissioning on a primary beam line of the JINR U-400M cyclotron. By means of nuclear fragmentation of the ^{14}N beam with the energy of 51 MeV·A on the 170 mg/cm^2 carbon target radioactive beams of ^6He, ^8He and ^8B were obtained. Possibilities of further development of the set-up are discussed.

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

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1. INTRODUCTION

The physics program in the reaction study with radioactive ion beams (RIB's) produced with the ACCULINNA facility will be devoted to the structure of light nuclei with neutron halo (^{6}He, ^{8}He, ^{11}Li) or nuclei with the expected proton halo (^{8}B), the isospin dependence of nuclear potential, fission of transuranium nuclei produced in fusion reactions of ^{8}He, ^{14}Be, ^{22}O and other neutron-rich RIB's, role of the neutron flow in fusion reactions of neutron-rich RIB's.

According to our estimations [1] the ACCULINNA design parameters allow to obtain on gaseous (H_2) or metallic (Be) production target, 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}.

In the near future systematic investigations of the lightest of the above mentioned nuclei, namely ^{6}He, will be started. In the framework of three body approach [2,3] this nucleus can be treated more easily than other halo nuclei since its components are structureless in a good approximation. Therefore revealing ^{6}He neutron halo as a knowledge of its characteristics can give an impetus to further theoretical and experimental investigations in this domain of nuclear physics.

The ^{6}He beams will be generated via the reaction $^{7}Li + {}^{1}H \Rightarrow {}^{6}He + 2p$. The beam of ^{7}Li ions accelerated in the charge state of 2^+ 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 order of $10^7 s^{-1}$.

To carry out this physics program a detection system is being developed which will consist of two telescopes on the base of multiwire proportional chambers, CsI(Tl) scintillation and Si detectors (ΔE Si strip detectors and thick Si(Li) detectors). The solid angle of a telescope is 100 msr. Such a detection system will give an opportunity to investigate elastic and inelastic scattering of ^{6}He nuclei with the sensitivity of $1 \cdot 10^{-28}$cm^2/sr and with the angular resolution of $\Delta\theta_{cm} \approx 5°$ in the centre of mass system. Some measurements, when it is needed, will be done with the angular resolution of $\Delta\theta_{cm} \approx 0.5°$. Energy resolution of CsI(Tl) and Si detectors will be at the level of $\leq 1\%$.

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 dimentions 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 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 Tale 1.

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 [4,5], 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. There 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 [6].

3. TEST EXPERIMENTS

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

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 3. The calculations were done under assumption of the isotropical and homogeneous distribution of the beam going 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 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 identified by a detector telescope consisting of a 300 μm 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.

In Fig.4 and Fig.5 are given beam matrices obtained when ACCULINNA was tuned to optimal production of $^{8}B^{5+}$ and $^{6}He^{2+}$ ions, respectively. As an example, the ^{6}He energy spectrum is presented in Fig.6. 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 really, 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 the data for ^{8}B produced without the wedge degrader. A small influence of the degrader on the ^{6}He yield is defined by its small thickness as applied to these more energetic ions in comparison with the ^{8}B ones. A considerable discrepancy between the predicted and experimental values of the ^{8}B yield seems to come from a corresponding overestimation of the reaction cross section used by the program.

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 = 1 mm. Second-order aberrations are taken into account.

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

RIB	without wedge		with wedge	
	Present data	Simulation	Present data	Simulation
ACCULINNA is tuned to ^8B				
^{12}N	-	$1.8\cdot10^4$	5	-
^{11}C	-	$4.7\cdot10^3$	52	-
^{10}C	-	$1.8\cdot10^4$	2	-
^9C	-	$4.9\cdot10^2$	5	160
^{10}B	-	$2.1\cdot10^2$	63	-
^8B	-	$9.7\cdot10^3$	$2.5\cdot10^2$	$3.5\cdot10^3$
^7Be	-	$1.7\cdot10^4$	$3.1\cdot10^3$	$7.1\cdot10^3$
^7Li	-	22	26	-
^6Li	-	$4.1\cdot10^3$	$9.1\cdot10^3$	$2.0\cdot10^3$
^4He	-	$3.9\cdot10^3$	$1.8\cdot10^3$	-
^3He	-	$5.7\cdot10^3$	-	-
ACCULINNA is tuned to ^6He				
^{11}Be	120	900	-	-
^{10}Be	12	61	10	38
^9Li	$3\cdot10^2$	$2.7\cdot10^3$	240	120
^8Li	$1.1\cdot10^3$	$4.7\cdot10^3$	$1.0\cdot10^3$	$3.2\cdot10^3$
^7Li	96	210	78	120
^8He	-	0.2	-	-
^6He	$1.4\cdot10^3$	$8.1\cdot10^3$	$1.3\cdot10^3$	$6.0\cdot10^3$
^4He	-	28	-	0.02

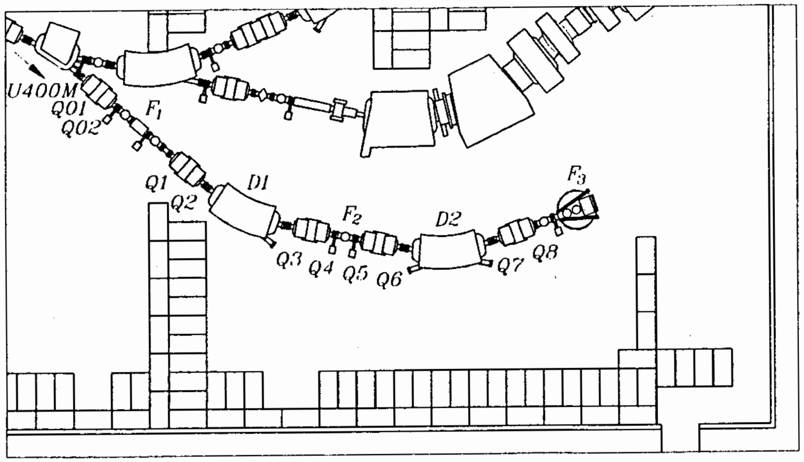

Fig. 1. The ACCULINNA layout.

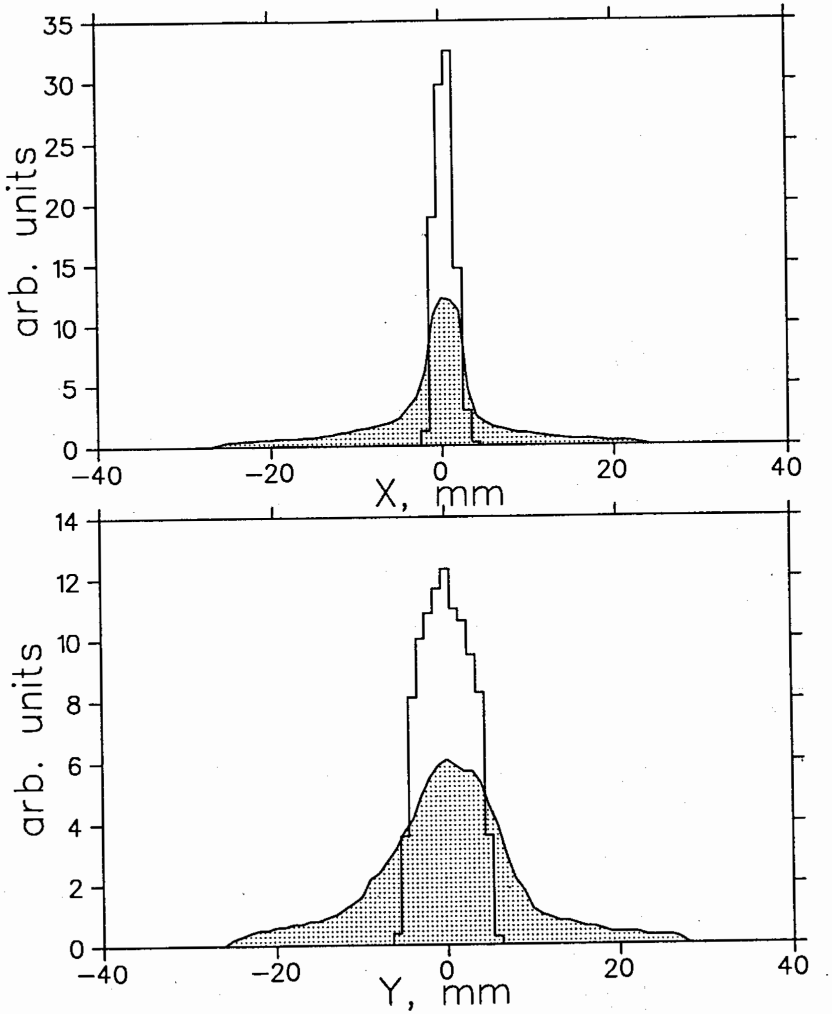

Fig. 2. The horizontal (top) and vertical (bottom) $^{14}N^{7+}$ beam profiles (dotted - measured, open - calculated) in the intermediate focal plane F_2. The measured FWHM widths Δx and Δy are 7 mm and 20 mm, respectively. The calculated profiles were simulated for the monochromatic beam. The main object slit was equal to 3×10 mm^2.

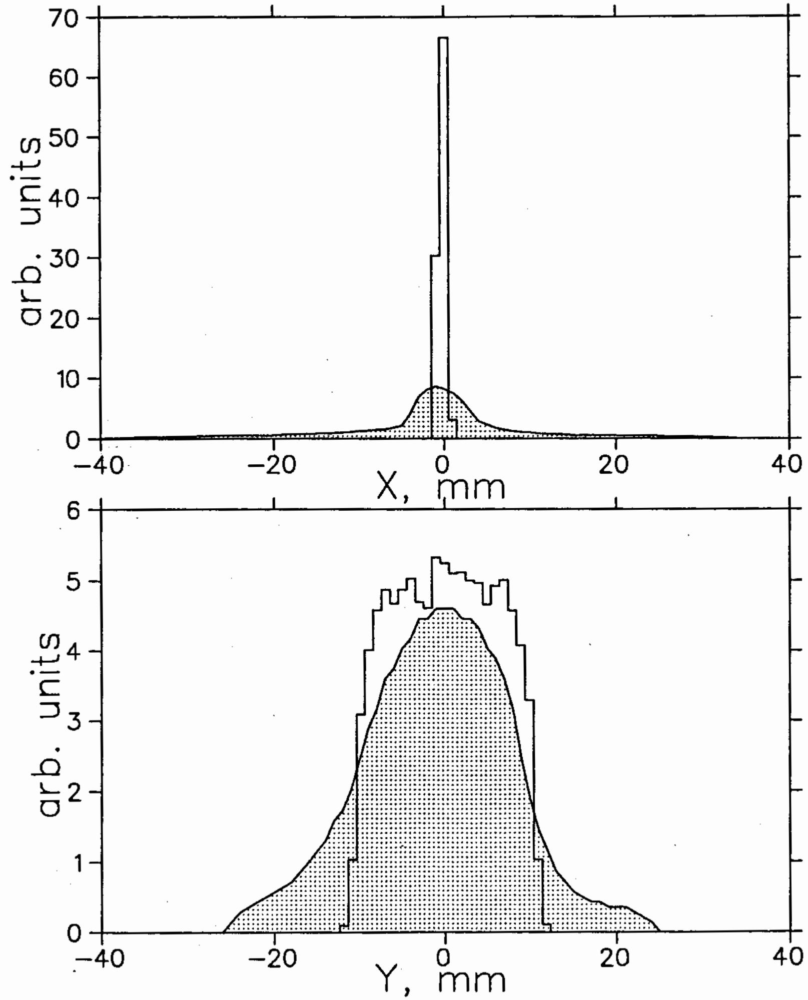

Fig. 3. The horizontal (top) and vertical (bottom) $^{14}N^{7+}$ beam profiles (dashed - measured, open - calculated) in the achromatic focal plane F_3. The measured FWHM widths Δx and Δy are 5 mm and 12 mm, respectively. The calculated profiles were simulated for the beam with the momentum spread of 1.3%. The object slit was as in Fig. 2.

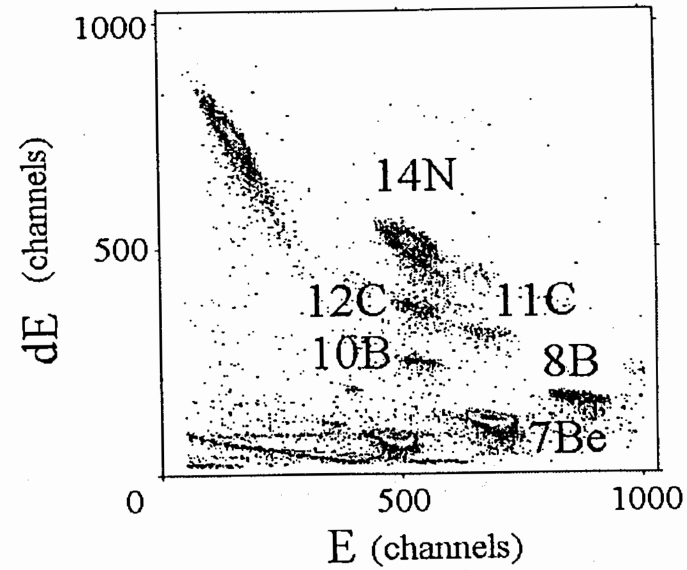

Fig. 4. ΔE-E beam matrix. The beam line was tuned to the optimal yield of ^8B ions.

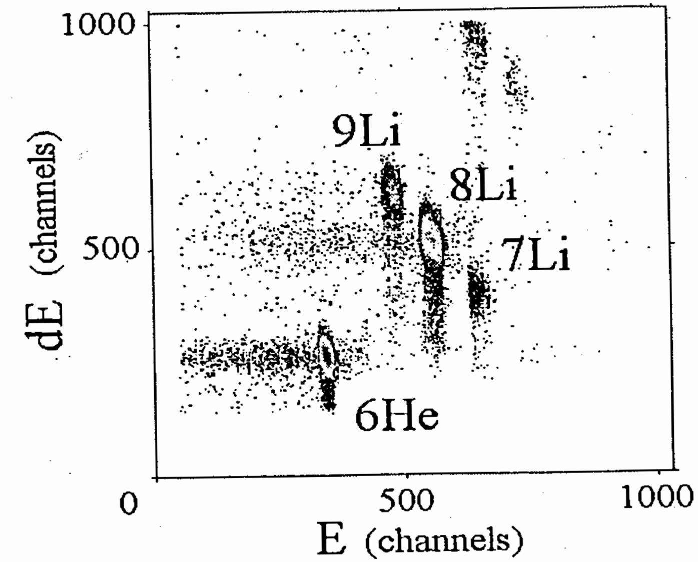

Fig. 5. ΔE-E beam matrix. The beam line was tuned to the optimal yield of ^6He ions.

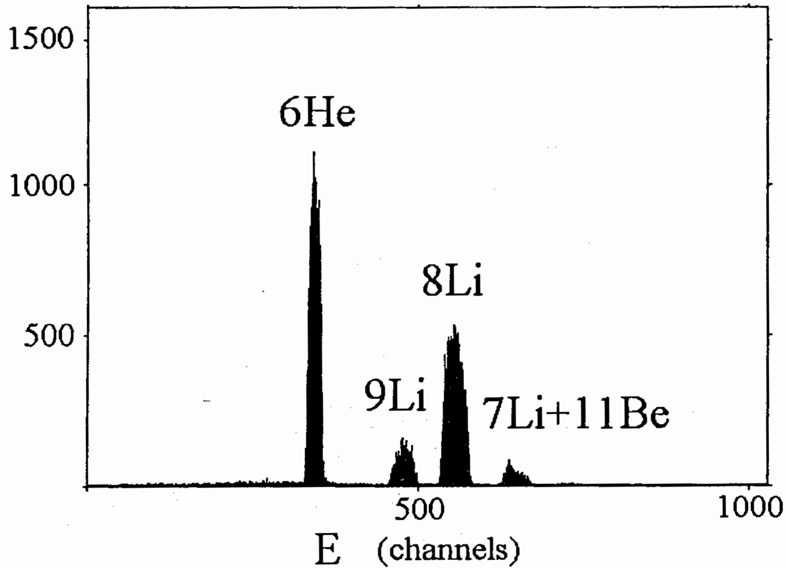

Fig. 6. Energy spectrum of the ^{6}He ions ($\Delta p/p$=2.9%(FWHM)).

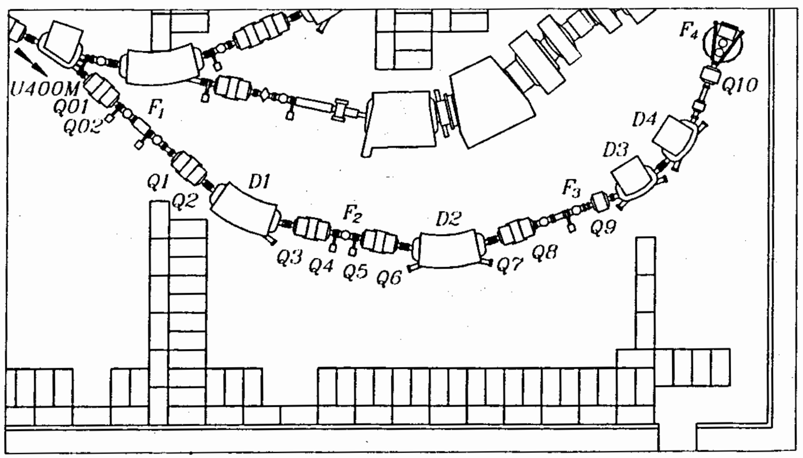

Fig. 7. The ACCULINNA future development.

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 interesties, 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 problem. Therefore, using even this badly non-optical reaction to produce ^{6}He beam, this ions with the intensity of about some factor of 10^4 pps can be obtained.

4. FUTURE DEVELOPMENT

The second phase of the project ACCULINNA consists in adding to the existing beam line a new transport line which will map the achromatic focal plane into a nonzero dispersion focal plane where both a good momentum resolution and small beam divergence will be present. In this case placing the physics target in this new focal plane and measuring the escape angle of reaction products one will be able to define more exactly the energy of the radioactive ions incident upon the physics target, hereby enhancing the energy accuracy of experiments as well as the precision measurements of angular distribution of reaction products.

In Fig.7 we shows the second stage of ACCULINNA which fits well the ion-optical conditions needed. This stage consists of two magnetic quadrupoles (Q9,Q10), two 22.5° dipole magnets (D3,D4) with the maximum magnetic rigidity of 3 T·m and a magnetic sextupole SX3 to rotate the focal plane F_4. This magnetic spectrometer permits to fix the focal plane momentum dispersion at the value of 20 mm/% while the horizontal linear magnification is varied in the range from 0.5 to 2, the vertical one does not exceed the value of 5 and the momentum angular dispersion is equal zero. These conditions are fulfilled by tuning the quadrupoles Q9 and Q10 in addition to the last quadrupoles Q7 and Q8 of the present facility. As calculation showed such a facility while conserving the transverse and longitudinal acceptances of the existing beam line will give an opportunity to perform nuclear physics experiments on radioactive beams with the energy resolution of about 0.3% and the angular beam divergence of ±5 mrad on the physics target.

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