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DEFLECTING SYSTEM UPGRADE INITIAL SIMULATIONS FOR 37 MeV CYCLOTRON AT NPI REZ

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Abstract

NPI Rez U-120M multi-particle variable energy cyclotron system for positive ions extraction consists of three electrostatic deflectors, one active magnetic channel and an electromagnetic bump exciter. The deflectors transmission ratio for deuterons, alpha particles and Helium 3 ions is rather low, usually about 10 %, for protons it is far below 5 %. Based on an experience from other cyclotron laboratories, the general concept of the extraction system has been modified and the last two electrostatic deflectors were replaced with two magnetic channels. In the early stage of the upgrade, simulations were performed for protons at 28 MeV and Helium 3 ions at 44 MeV with and without the magnetic bump exciter. The extraction efficiency and beam losses along the extraction path are evaluated. The presented modified extraction system simulations suggest promising results. The total transmission ratio of the deflecting system has increased significantly, allowing work to continue and expect a positive final result.

ACTUAL SITUATION OVERVIEW

The isochronous cyclotron U-120M is a four sector machine with a pole diameter 120 cm, 18 trim coils. It is in operation from 1977. Initially it was built in JINR as a positive ions accelerator, an option for negative ions was enabled circa 15 years later. Complete list of accelerated ions with their maximal energies is specified in Table 1. For both ion polarities an internal cold cathode Penning type ion source is used. The negative ions are extracted using a stripping foil with efficiency close to 100 %.

The extraction of positive ions is rather problematic and requires a significant improvement. There are two main issues related to the low extraction ratio. Firstly, it is the low extracted beam current, but usually this can be compensated by a prolonged irradiation time. Secondly, it is very high activation of the cyclotron equipment, especially the extraction elements, which prevents an efficient maintenace.

Table 1: Possible positive ions with their energy ranges and maximal internal currents at the U-120M cyclotron.

Particle	Energy range	Maximal current int.
protons	6 – 37 MeV	200 µA
deuterons	7 – 20 MeV	80 µA
α	12 – 40 MeV	40 µA
$^3He^{2+}$	17 – 54 MeV	20 µA

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Extraction System Concept

The original concept of the extraction system described in [1] is shown in Fig. 1. The system had consisted of an electrostatic first harmonic exciter (EE) and an electrostatic compensator (EC), three electrostatic deflectors (ESD) and one magnetic channel after ESD III (not in figure). Extraction efficiency of this configuration was close to 40 %. After the compensator part failed, the electrostatic exciter was replaced by a magnetic bump coil. This change was made in about 1980 and the extraction efficiency had dropped significantly.

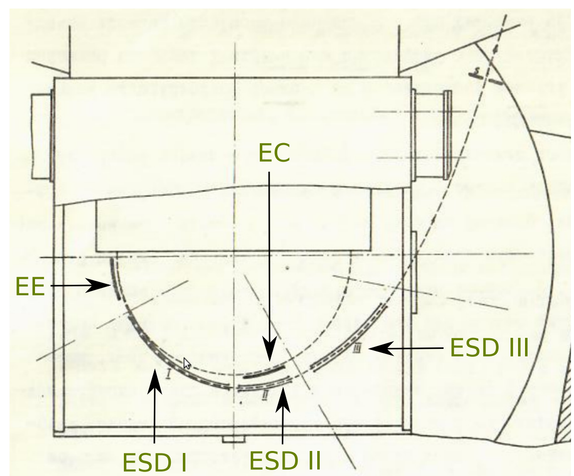

Figure 1: The original concept of the extraction system [1].

Electrostatic Deflectors

The system consists of three ESD's located at azimuths 120°, 182° and 215°. Septum of the first electrostatic deflector is placed near extraction radius 510 mm where ν_r is still ~1.03.

The original intention was that the electrostatic deflectors would also have vertical beam focusing properties. This resulted in their rather complicated shape (see Fig. 2). Moreover the first ESD is divided into a part for the beam deflection and a part for the beam deflection and vertical focusing. The nontrivial shape of the septums and electrodes are responsible for a part of the high extraction losses. Second part is due high radial beam dispersion, as the beam passes all three deflectors without any kind of radial focusing.

Magnetic Field Bumper

The beam is extracted by a Brute force method as the $\nu_r = 1$ region is crossed very fast [2]. The magnetic bump coil is a dipole magnet with the center at azimuth 98°, 12°

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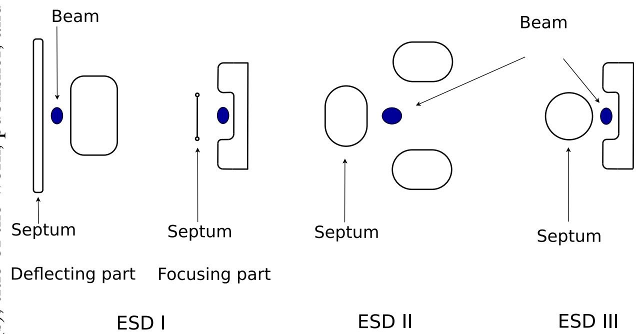


Figure 2: Eletrostatic deflectors profiles. Not labeled profiles belongs to high voltages electrodes.

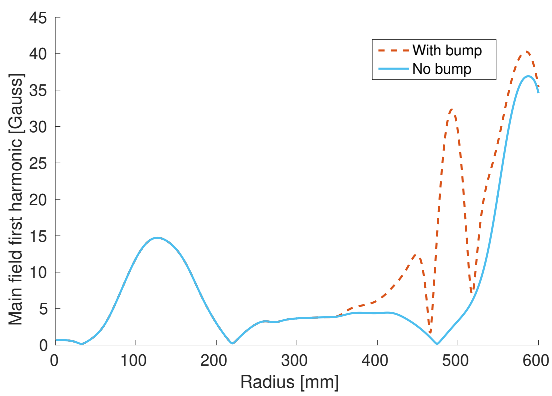


Figure 3: First harmonic introduced by the magnetic field bumper at proton regime for 28 MeV.

width and with a variable radial position 460 mm–500 mm. The introduced magnetic field perturbation is not compensated resulting in a slight phase shift of the accelerated beam. The influence of the bump magnet to the first harmonic component of the main magnetic field is shown in Fig. 3.

Harmonic Coils

The U-120M cyclotron has two sets of harmonic coils. Internal coils are placed at radius 140 mm and are used for the beam centering. Outer harmonic coils are placed at radius 420 mm, too far from the extraction radius 510 mm. They were originally not intended as extraction coils and currently they are not in operation.

SIMULATIONS

Beam dynamic simulations were performed in an "in house" Durycnm18 code [3] and in the SNOP – free to use beam analysis code for compact cyclotrons [4]. Durycnm18 was used for proper beam centering and the magnetic bump amplitude and radial position tuning. The SNOP code was used for phase slits influence evaluation, deflector septum and magnetic channels optimization and a beam loss analysis.

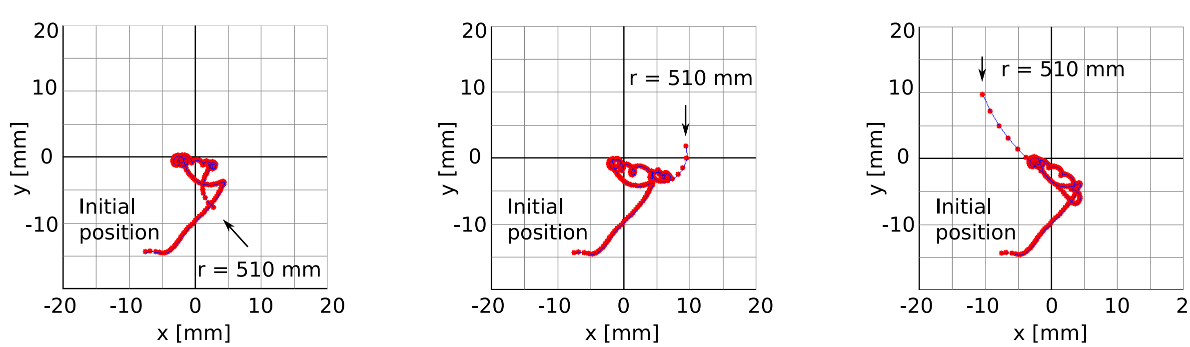
Two regimes were used for the transmission ratio calculations, protons at 28 MeV and $^3He^{2+}$ at 44 MeV as they are about 80 % of the maximal energy. Based on other laboratories experience, the general concept of the extraction system has been modified. The ESD II and ESD III were replaced by analytically introduced magnetic channels MC, which provide radial beam focusing. With this configuration, three basic modifications of the extraction system were evaluated:

- Bump coil was turned off. Beam extracted without additional separation.
- Bump coil was replaced by a short ESD 0. Outer harmonic coils used for a turn separation. Phase slits introduced to the cyclotron central region.
- Bump coil used for the turn separation and phase slits introduced to the central region.

Beam Centering

Good beam centering can be obtained for the central particle by fine tuning of the inner harmonic coils. Surrounded RF phases are well centered for about ± 15°, depending on the accelerated ion type and its final energy. With proper centering, the beam radial size is about 2.5 mm at the ESD enter. Beam center coordinates for the three above mentioned modifications are show in Fig. 4.

It seems that there is a natural first harmonic at azimuth 270° in the magnetic field. As the deflector is located at



(a) Centered beam. Intrinsic first harmonic at azimuth ~270°.

(b) Centered beam with outer harmonic coils. Center shifts to azimuth ~70°.

(c) Centered beam with the field bump at azimuth 98°.

Figure 4: Beam center coordinates for the central RF phase and different harmonic coil settings. Septum of the first deflector located at azimuth 113.5°.

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113.5°, this intrinsic field perturbation push the beam just the opposite direction. The intrinsic first harmonic can be observed in Fig. 3 where it starts at radius 480 mm and also in Fig. 4a as a tail of the beam center path.

Phase Slits

Phase slits introduced into the central region need to respect the actual geometry and space restrictions in the area. In past years there was an attempt to introduce the phase slit as one piece slit placed in the central region. Resulting beam properties were not satisfactory and the phase slit idea was abandoned. By a detailed analysis of the central region, we observed a better solution. It is beneficial to split the phase slit into two separate parts, placed at different positions in the central region. Respecting the necessity of remote position controlling, there are only two possible locations. First is in the region of the ion source head, at the first orbit, where the slit limits lower RF phases. Here the phase slit position control can be done by a piston-rod hidden in the ion source support. Second position is inside the puller at the second beam orbit, where the upper RF phases are restricted. By a proper phase slits setting it is possible precisely tune the beam RF phase range leaving the central region. Figure 5 shows comparison of the initial and accelerated beam RF phase distribution for the phase slits setting ±15° around the central RF phase −7°.

We afraid that the second phase slit position control could be a difficult mechanical and engineering task, as it is placed inside the puller. Nevertheless its use is highly appreciated. We consider a hydraulic driving of the second phase slit.

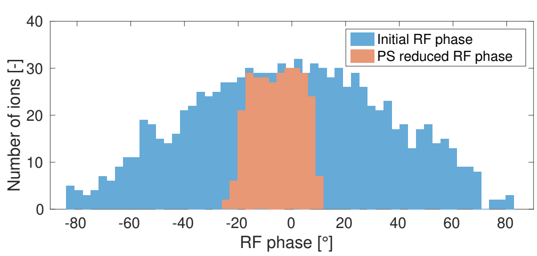

Figure 5: RF Phase distributions for initial and for the accelerated beam.

Turn Separation

Without using the field bump or the outer harmonic coils, the beam is not separated at the extraction radius 510 mm and aziuth 114° at all. Experimentally, we switched on the external harmonic coils and evaluated their benefit to the extraction process. The beam center at the extraction radius is shifted towards aziuth ~70° as can be seen in Fig. 4b. Results were promising for part of the acceleration regimes, but not for all.

Better results are achieved using the bump magnet, for which the degree of the turn separation is similar to the effect ot the outer harmonic coils, but the azimuth is more appropriate. Plot of orbits from radius 470 mm with the turns separated by the bump coil is in Fig. 6. Corresponding beam centering is plotted in Fig. 4c.

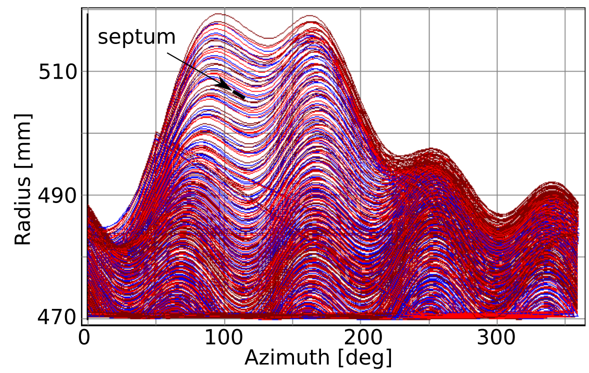

Figure 6: Orbit separation at azimuth 110° by a magnetic field bump and ESD septum position.

Extraction Elements

At this early stage of the U-120M extraction system upgrade, the extraction elements are simulated using analytical electromagnetic fields inserted into the acceleration region. In the future, when CAD models of the deflector and magnetic channels will be created and simulated, their real fields will replace the analytical fields.

The deflector septum shape is derived from the central particle path and its CAD model is inserted to the SNOP code for particle losses evaluation.

SIMULATION RESULTS

For the case without an additional turn separation, i.e. when the bump coil was turned off, we were not able to reach extraction ratio better than 40%. This is partly caused by not using the phase slits to reduce the RF width of the beam. After we introduced the phase slits and improved the turn separation by using the outer harmonic coils, we also tried to introduce short electrostatic deflector ESD 0 before ESD I, instead of the bump coil. Transmission ratio improves dramatically, but at some regimes the effect was not beneficial.

Best results were achieved by using the phase slits in the central region and the bump coil together. In this case we prolonged the first electrostatic deflector by 6° moving its beginning to azimuth 113.5°. One optimized septum shape was used for both evaluated regimes, just with different positions and angles. Results of this third modification are presented in the Table 2, where initial vs. accelerated beam stands for the beam leaving the ion source vs. the beam after the phase slits. Emittances are calculated for two standard deviations of the mean. The transmission ratio was evaluated at the cyclotron output to a beam transmission line located at radius ~1050 mm. No losses are considered in the magnetic channels. The magnetic channels settings were optimized for a proper beam focusing.

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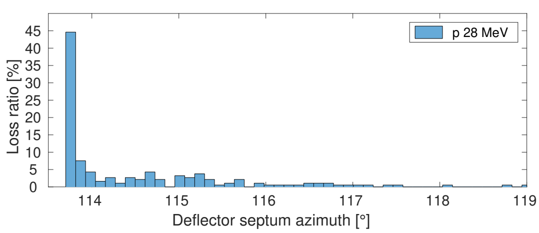
Table 2: Simulation Results

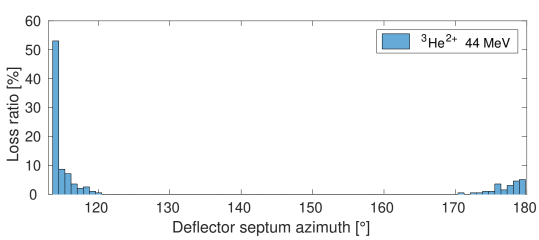
		p 28.0 MeV	$^3He^{2+}$ 44.0 MeV
RF phase beam width		30°	55°
Central RF phase		−7°	−2°
Extracted beam radial emittance		7.8 π mm mrad	13 π mm mrad
Extracted beam vertical emittance		0.9 π mm mrad	1.1 π mm mrad
Losses on septum	From initial beam :	3.5 %	3.6 %
	From accelerated beam:	11.8 %	7.1 %
ESD transmission ratio	From initial beam:	25.8 %	47.9 %
	From accelerated beam:	88.2 %	2.9 %

Losses Distribution

Figure 7 shows comparison of the septum losses distribution for the two compared regimes. The proton 28 MeV regime has the major part of beam loss located at the beginning of the septum and the rest on the first few centimeters (see Fig. 7a). On the other end for the $^3He^{2+}$ at 44 MeV regime, the septum touches the beam also with its end, as can be seen in Fig. 7b. This can be further optimized by a small change of the septum shape or by further decrease of the RF phase beam width.



(a) Regime for p 28 MeV. Detail of the septum beginning.



(b) Regime for 3He^{2+} 44 MeV. Full septum length.

Figure 7: Losses distribution along the electrostatic deflector septums for two evaluated regimes.

CONCLUSION

For the intended positive particles extraction system upgrade at the U-120M cyclotron, three basic modifications of the current configuration were simulated. Mode without an additional turn separation by the bump coil, a mode using the outer harmonic coils for the turn separation with a short electrostatic deflector ESD 0 instead of the bump coil and a mode using the bump coil for the turn separation and slightly prolonged the first electrostatic deflector ESD I were compared. Surprisingly the best results were obtained for the configuration with the bump coil. We originally thought the bump coil is not suitable for the extraction, but with a proper beam RF phase reduction, its use is justified. It now seems necessary to install the phase slits in the cyclotron central region. The simulated first electrostatic deflector transmission ratio increased significantly, for both regimes close to one order.

By replacing the second and the third electrostatic deflector by magnetic channels for an additional radial focusing, also a considerable increase in the total extracted beam can be expected.

In the next step we will concentrate on a design of suitable magnetic channels as they will be an indispensable part of the final extraction system.

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