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# SIMULATION OF THE AXIAL INJECTION BEAM LINE OF THE RECONSTRUCTED U200 CYCLOTRON OF FLNR JINR

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## INTRODUCTION

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research begins the works under the conceptual design of Radiation Facility based on the DC130 cyclotron [1], that will be created as a deep reconstruction of the old cyclotron U200 [2]. Main parameters of DC130 cyclotron presents Table 1.

Table 1: DC130 cyclotron main parameters

| | | |
|---|---|---|
| Pole (extraction) radius, m | 1(0.88) | |
| Magnetic field, T | 1.729÷1.902 | |
| Number of sectors | 4 | |
| RF frequency, MHz | 10.622 | |
| Harmonic number | 2 | 3 |
| Energy, MeV/u | 4.5 | 1.993 |
| A/Z range | 5.0÷5.5 | 7.577÷8.0 |
| RF voltage, kV | 50 | |
| Number of Dees | 2 | |
| Ion extraction method | electrostatic deflector | |
| Deflector voltage, kV | 60 | |

The radiation facility will be used for Single Event Effect (SEE) testing of microchips by means of ion beams ($^{16}$O, $^{20}$Ne, $^{40}$Ar, $^{56}$Fe, $^{84,86}$Kr, $^{132}$Xe, $^{197}$Au and $^{209}$Bi) with energy of 4.5 MeV per unit mass and having mass-to-charge ratio A/Z in the range from 5.0 to 5.5.

Besides the research works on radiation physics, radiation resistance of materials and the production of track membranes will be carrying out by using the ion beams with energy of about 2 MeV per unit mass and A/Z ratio in the range from 7.58 to 8.0.

The acceleration of ion beam in the cyclotron will be performed at constant frequency f = 10.622 MHz of the RF-accelerating system for two different harmonic num-bers h. The harmonic number h = 2 corresponds to the ion beam energy W = 4.5 MeV/u and value h = 3 corresponds to W = 1.993 Mev/u. The intensity of the accelerated ions will be about 1 pμA for lighter ions (A<86) and about 0.1 pμA for heavier ions (A>132).

The axial injection system of DC130 cyclotron will be adapted from the existing IC100 cyclotron one [3].

This report presents the simulation of the beam dynamic in the axial injection beam line of DC130 cyclotron. The simulation was carried out by means of MCIB04 program code [4].

## ECR ION SOURCE

The ion beams are produced in superconducting ECR ion source DECRIS-SC designed in Flerov Lab of JINR [5]. The working frequency DECRIS-SC is equal to 18 GHz. It is able to produce the beams of ion from 22Ne to 209Bi. The ion beam currents at the source exit sufficient for the facility operation is contained in Table 2.

Table 2: Ion beam current extracted from DECRIS-SC

| Ion | Current pmcA | Ion | Current pmcA |
|---|---|---|---|
| $^{22}Ne^{4+}$ | ~ 50 | $^{132}Xe^{23+}$ | ~ 4 |
| $^{40}Ar^{7+}$ | ~ 30 | $^{132}Xe^{24+}$ | ~ 4 |
| $^{56}Fe^{10+}$ | ~ 4 | $^{197}Au^{34+}$ | ~ 0.3 |
| $^{84}Kr^{15+}$ | ~ 8 | $^{209}Bi^{37+}$ | ~ 0.2 |

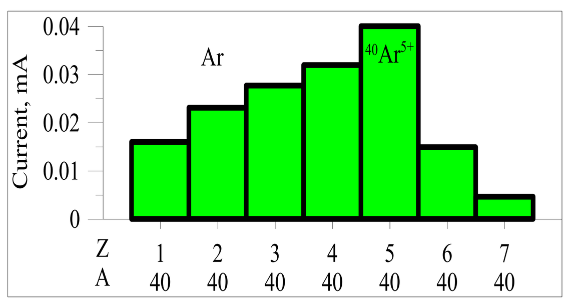


Figure1: Ar beam current distribution

The charge state distribution of argon beam current used in simulation is shown in Fig.1.

In adaptation, the distance between extraction hole of the ion source and first focusing solenoid of transport beam line will be reduced significantly to avoid the losses of the ion beam.

The parameters of the ion beams at the extraction hole of ECR ion source are contained in Table 3.

Table 3. Parameters of ion beam used in simulation

| Injected ions | $^{209}Bi^{38+}$ | $^{40}Ar^{5+}$ |
|---|---|---|
| A/Z | 5.5 | 8.0 |
| Extraction voltage $U_{inj}$, kV | 16.8 | 10.9 (17.3) |
| Beam current [μA] | 10 | 40 |
| Beam diameter, [мм] | 8 | |
| Emittance, π mm×mrad | 217 | 225 (180) |

## BEAM LINE SCHEME

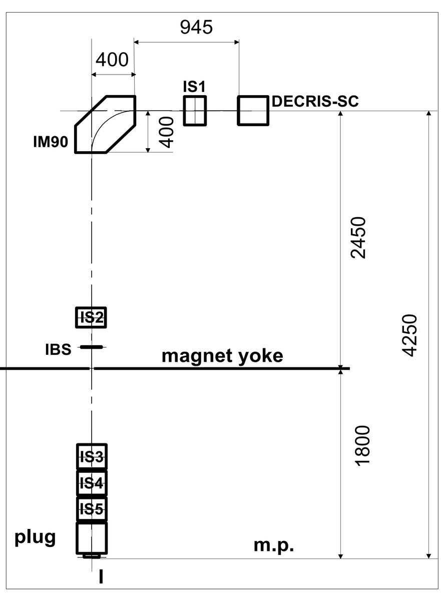


Figure 2: Scheme of axial injection beam line

The length of the beam line is equal to 5.423 m. The 90-degree analyzing magnet IM90 separates the injected beam. The solenoidal lenses IS1-5 focus and match beam with the acceptance of the spiral inflector I for all level of the magnetic field. The sinusoidal buncher IBS increases the beam capture into acceleration.

## ANALYZING MAGNET IM90 AND SOLENOIDS IS1,2

Analyzing magnet IM90 and solenoids IS1,2 are the part of existing IC100 cyclotron axial injection beam line [3]. The analyzing magnet IM90 has a bending radius $R_M$ equal to 0.4 m and maximum magnetic field 0.16 T. The maximum magnetic field induction of solenoids IS1,2 is equal to 0.5 T.

## SOLENOIDS IS3-5

The distribution of the magnetic field in the channel depends significantly on its magnitude at the center of the cyclotron $B_0$ (see Fig. 3). The scheme of solenoids IS3-5 is presented in Fig.4.

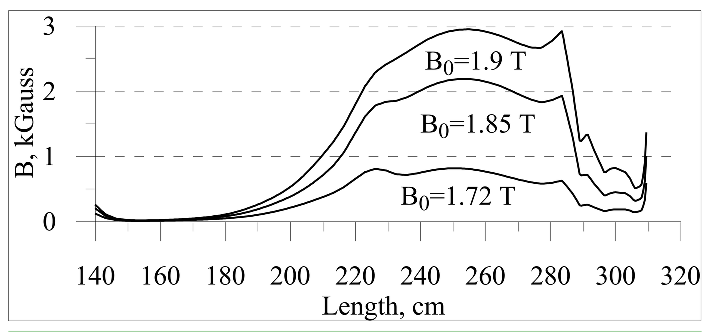


Figure 3:Cyclotron field distribution in beam line

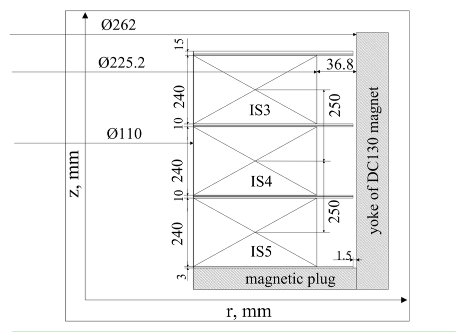


Figure 4:Scheme of solenoids IS3-5

At low levels of the magnetic field it is necessary to use a focusing solenoid placed at the minimum distance from the median plane of the cyclotron magnet (IS5 in Fig.2) [6]. At high levels, the cyclotron magnetic field strongly focuses the beam and it needs to be compensated by means of additional solenoids (IS3,4 in Fig.2) as in the axial injection channel of the U-400M cyclotron [6].

The diameter of the hole in the yoke of the U200 magnet is equal to 136 mm. This does not allows placing solenoids with the maximum magnetic field induction greater than 1.5 kGauss. The diameter of the hole should be increased up to 262 mm that will give opportunity to achieve the necessary field magnitude for internal diameter of the vacuum tube 100 mm.

Table 2 contains the parameters of solenoids IS3-5. Fig.5 gives the on-axis distribution of the magnetic field of solenoids IS3-5.

Table 2. Solenoids parameters

| | |
|---|---|
| Maximum induction, kG | 3.38 |
| Turn number | 150 |
| Winding resistance, Ohm | 0.031 |
| Current, A | 450 |
| Voltage, V | 14.0 |
| Power supply, kW | 6.3 |

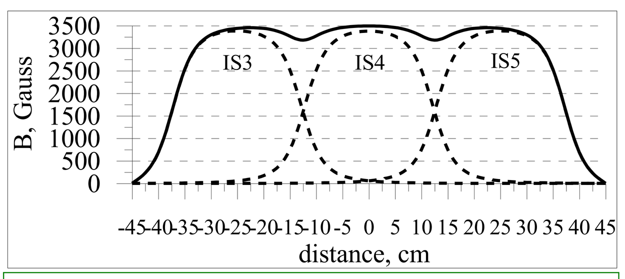


Figure 5:On-axis magnetic field of solenoids

## MAGNETIC PLUG AND SPIRAL INFLECTOR I

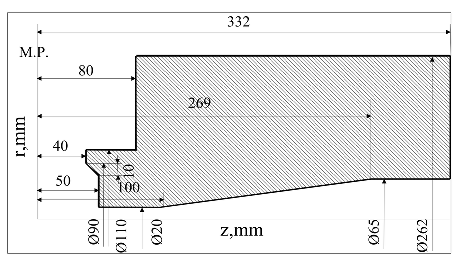

Figure 6:Magnetic plug scheme

To ensure 100% efficiency of ion beam transfer, it is necessary to change the aperture of the magnetic plug. The scheme of proposed magnetic plug is shown in Fig.6.

The magnetic radius of the spiral inflector $r_m$ is chosen equal to 2.3 cm. In the case of harmonic number h = 2, the ECR extraction voltage $U_{inj}$ varies from 15.26 kV to 16.79 kV for ions having A/Z in the range 5.0 ÷ 5.5.

While, in the case of h=3 extraction voltage will not exceed 10.9 kV for injecting ions having A/Z in the range 7.57 ÷ 8.0 . This leads to an increase of the emittance of the injected beam and a decrease of the beam bunching efficiency, because of the increasing of the beam self field.

Therefore, in the case h = 3 it is desirable to work with a second magnetic inflector having an magnetic radius increased up to 2.9 cm. The extraction voltage will then be in the range $U_{inj}$ = 16.3 kV ÷ 17.3 kV.

## SINUSOIDAL BUNCHER IBS

To improve the efficiency of beam capture into the acceleration mode a sinusoidal (one harmonic) buncher IBS, located outside the yoke of the magnet at a distance of 2.0 m from the median plane of the cyclotron, is used. The maximum applied voltage at the grids of buncher is 480 V for the injecting ions having A/Z = 5.5. The efficiency of bunching varies from 1.6 to 2.1 ( Fig.7-9).

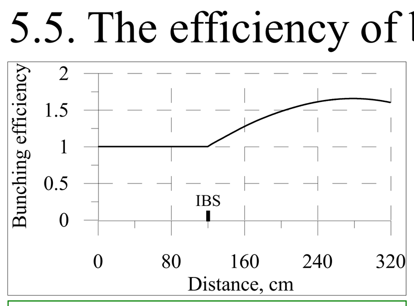


Figure 7: Bunching efficiency. $^{40}Ar^{5+}$ beam transport, $r_m$ = 2.3 cm

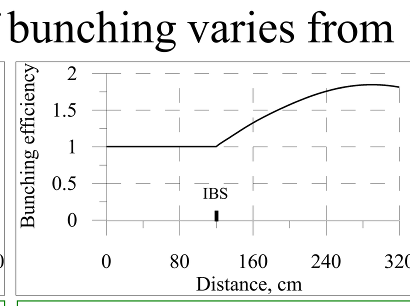


Figure 8: Bunching efficiency. $^{40}Ar^{5+}$ beam transport, $r_m$ = 2.9 cm

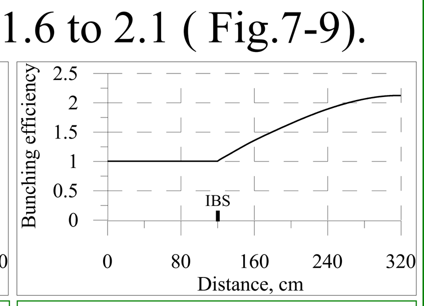


Figure 9: Bunching efficiency. $^{209}Bi^{38+}$ beam transport, h = 2

## SIMULATION RESULTS

Simulation of ion beam injection in the cases A/Z = 5.5, 8.0 are carried out. For the maximum value of A/Z= 8 two variants of the spiral inflector were considered. In all cases, the transfer efficiency is equal to 100%.

*A/Z=5.5, $B_0$=1.902 T, $r_m$ = 2.3 cm*

Transport of $^{209}Bi^{38+}$ ion beam was considered. In this case the magnetic field at the center of the cyclotron $B_0$ = 1.9021 T is maximal. The focusing solenoid IS5 is turned off ($B_{IS5}$ = 0) and the matching with acceptance of the inflector is performed by focusing solenoid IS2 and compensating ones IS3,4 ($B_{IS2}$ = 1.906 kG, $B_{IS3}$ = $B_{IS4}$ = -1.930 kGs).

Figure 9 shows the cyclotron field (red line) and the total field of the cyclotron and focusing solenoids (black line).

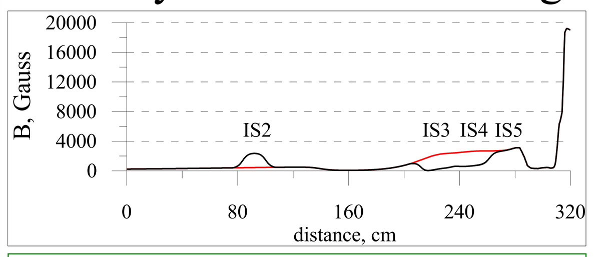


Figure 9:Magnetic field in vertical part of beam line. $^{209}Bi^{38+}$ ion beam transport.

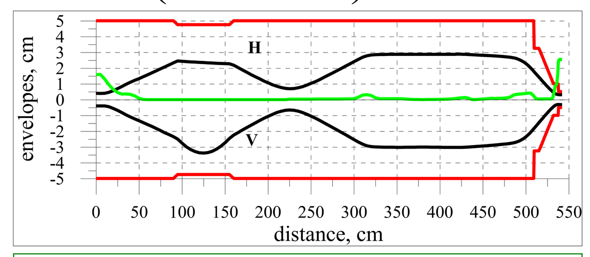


Figure 10:$^{209}Bi^{38+}$ ion beam envelopes.

The horizontal (H) and vertical (V) envelopes of $^{209}Bi^{38+}$ ions in the beam line is shown in Fig.10. The beam envelopes in vicinity of magnetic plug and inflector are presents in Fig.11. The dependence on distance along the beam line of the beam emittance is shown in Fig.12.

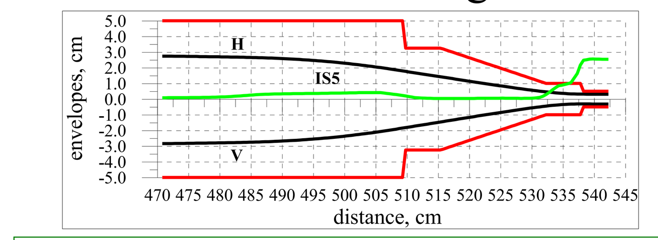


Figure 11: $^{209}Bi^{38+}$ ion beam envelopes near inflector.

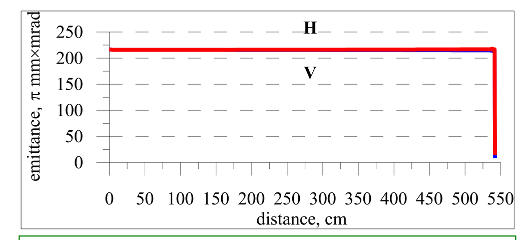


Figure 12: $^{209}Bi^{38+}$ ion beam emittances.

*A/Z=8.0, $B_0$=1.845 T, $r_m$ = 2.3 and 2.9 cm*

Transport of $^{40}Ar^{5+}$ ion beam was considered. In the both cases the magnetic field at the center of the cyclotron $B_0$ = 1.8445 T. The compensating solenoids IS3,4 are switched on ($B_{IS3}$ = $B_{IS4}$ = -2.0 kGs) and matching with the inflector acceptance is provided by solenoids IS2,5 ($B_{IS2}$ = 2.519 kG, $B_{IS5}$ = 1.209 kG). Fig. 13 shows the cyclotron field (red line) and the total field of the cyclotron and focusing solenoids (black line). The horizontal (H) and vertical (V) envelopes of $^{40}Ar^{5+}$ ions in the beam line is shown in Fig.14,15. Changing of the emittance in the beam line is shown in Fig.16.

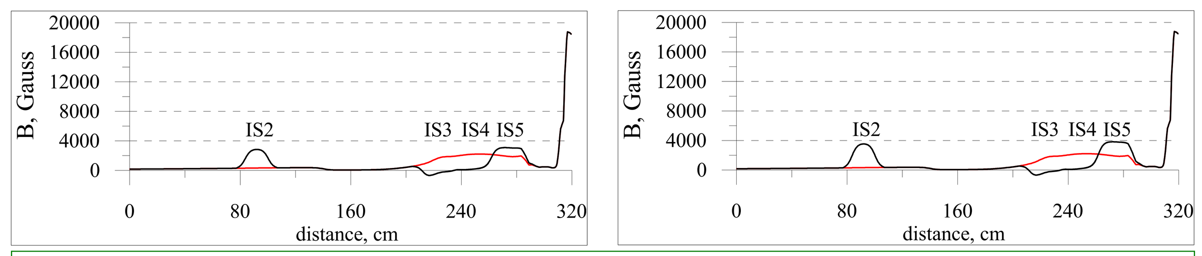


Figure 13: $^{40}Ar^{5+}$ ion beam. Magnetic field in beam line; Left $r_m$= 2.3 cm; Right $r_m$ = 2.9 cm

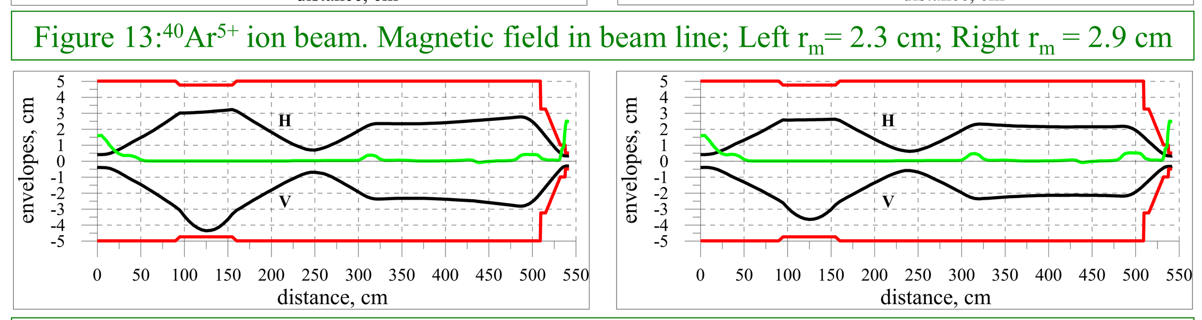


Figure 14: $^{40}Ar^{5+}$ ion beam. Beam envelopes; Left $r_m$= 2.3 cm; Right $r_m$ = 2.9 cm

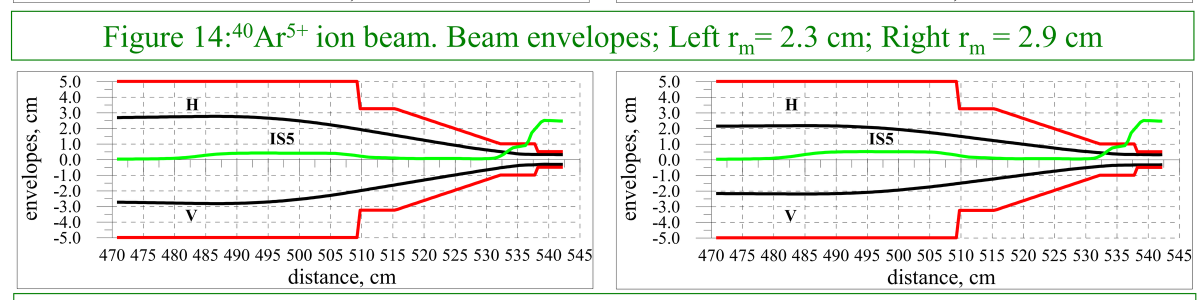


Figure 15: $^{40}Ar^{5+}$ ion beam. Beam envelopes near inflector; Left $r_m$= 2.3 cm; Right $r_m$ = 2.9 cm

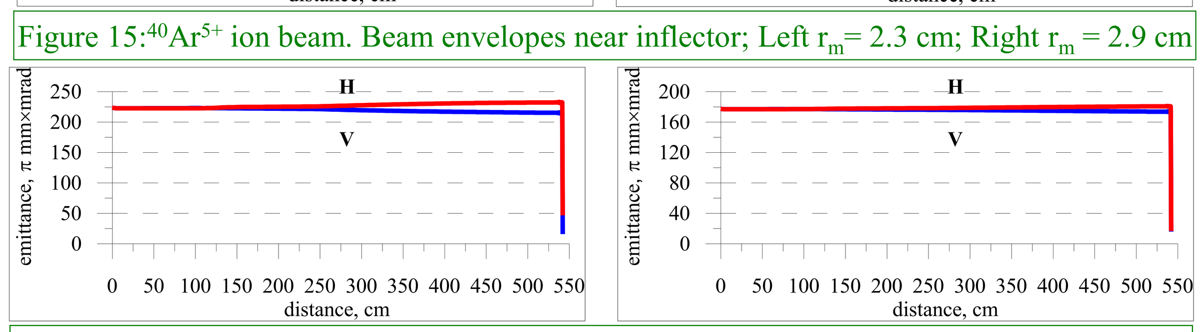


Figure 16: $^{40}Ar^{5+}$ ion beam. Beam emittances; Left $r_m$= 2.3 cm; Right $r_m$ = 2.9 cm

## SUMMARY

The axial injection system of DC130 cyclotron allows transporting with of 100% efficiency all ion beams declared in the project of Radiation Facility [1].

The comparison of simulation results shows the advantage of using the spiral deflector with increased up to 2.9 cm magnetic radius under work of RF with ion beams of low energy (W = 1.993 MeV/u).

The maximum magnetic field induction of solenoids IS3-5 is not greater than 2.0 kGauss. This gives opportunity to decrease the diameter of the hole in the yoke of the magnet by decreasing the number of layers and outer diameter of solenoidal winding.

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