SIMULATION OF THE AXIAL INJECTION BEAM LINE OF DC140 CYCLOTRON OF FLNR JINR

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INTRODUCTION

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research carries out the works under the creating of Irradiation Facility based on the DC140 cyclotron. The DC140 will be a reconstruction of the DC72 cyclotron [1,2]. Table 1 presents the main parameters of DC140 cyclotron

Table 1: DC140 cyclotron main parameters

Pole (extraction) radius, m	1.3(1.18)	
Magnetic field, T	1.415÷1.546	
Number of sectors	4	
RF frequency, MHz	8.632	
Harmonic number	2	3
Energy, MeV/u	4.8	2.124
A/Z range	5.0÷5.5	7.577÷8.25
RF voltage, kV	60	
Number of Dees	2	
Ion extraction method	electrostatic deflector	
Deflector voltage, kV	70	

The irradiation 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 4.8 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 2.124 MeV per unit mass and A/Z ratio in the range from 7.577 to 8.25.

The working diagram of DC140 cyclotron is shown in Fig.1. The acceleration of ion beam in the cyclotron will be performed at constant frequency f = 8.632 MHz of the RF-accelerating system for two different harmonic numbers h. The harmonic number h = 2 corresponds to the ion beam energy W = 4.8 MeV/u and value h = 3 corresponds to W = 2.124 Mev/u. The intensity of the accelerated ions will be about 1 pμA for light ions (A ≤ 86) and about 0.1 pμA for heavier ions (A ≥ 132).

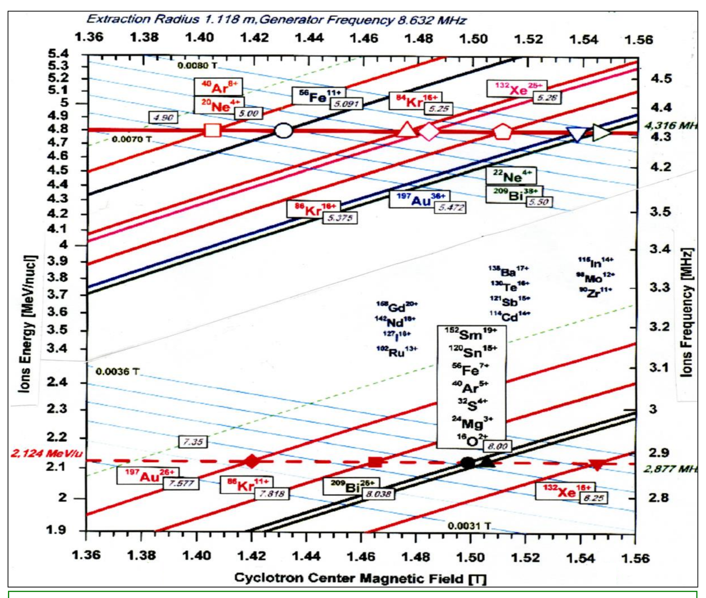

Figure1:Working diagram of DC140 cyclotron

The axial injection system of DC140 cyclotron will be adapted from the existing DC72 cyclotron one [3]. This report presents the simulation of the beam dynamic in the axial injection beam line of DC140 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 ^{22}Ne to ^{209}Bi. The ion beam currents at the source exit sufficient for the facility operation are 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

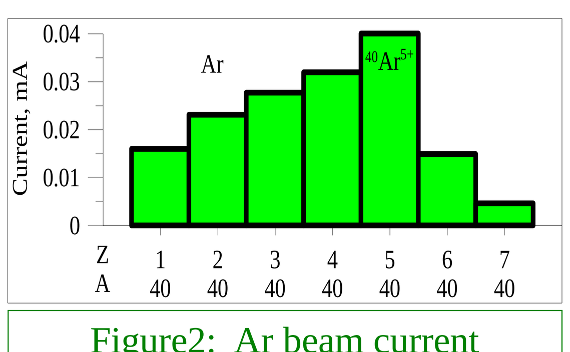

Figure2: Ar beam current distribution

The charge state distribution of argon beam current used in simulation is shown in Fig.2.

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	$^{209}Bi^{38+}$	$^{132}Xe^{16+}$
A/Z	5.5	8.25
Extraction voltage U_{inj}, kV	17.26	14.31
Beam current [μA]	10	
Beam diameter, [мм]	8	
Emittance, π mm×mrad	225	200

BEAM LINE SCHEME

The scheme of the beam line is shown in Fig. 3. The length of the beam line is equal to 5.018 m. The 90-degree analyzing magnet IM90 separates the injected beam. The solenoidal lenses IS1-4 focus and match beam with the acceptance of the spiral inflector I for all level of the cyclotron magnetic field. The sinusoidal buncher IBN increases the beam capture into acceleration. Two movable diaphragms ID1,2 are used for analysis of the beams spectra.

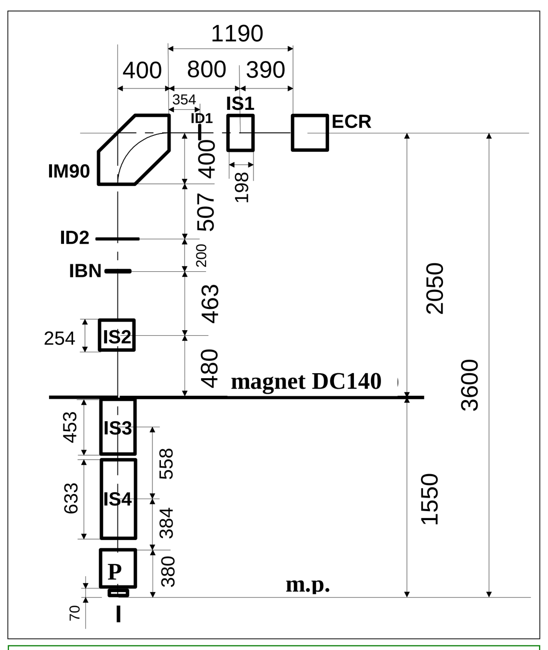

Figure 3: Scheme of axial injection beam line

ANALYZING MAGNET IM90

The analyzing magnet IM90 has a bending radius RM equal to 0.4 m, gap 80 mm and maximum magnetic field 0.2 T. This magnet was used in U400M cyclotron axial injection beam line before it upgrading

SOLENOIDS IS1-4

The solenoids IS1-4 are the part of existing DC72 cyclotron axial injection beam line [3]. Its on-axis magnetic fields are shown in Fig.4.

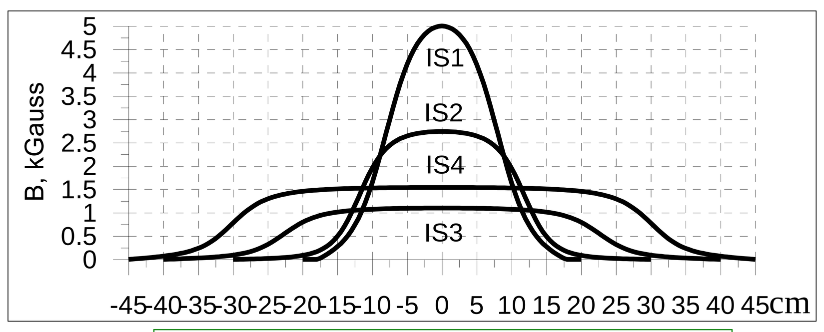

Figure 4:On-axis magnetic field of solenoids

MAGNETIC PLUG

The parameters of the magnetic plug (P in Fig.3.) of the DC72 cyclotron were used in the calculation. The channel aperture in plug is shown in Fig.5.

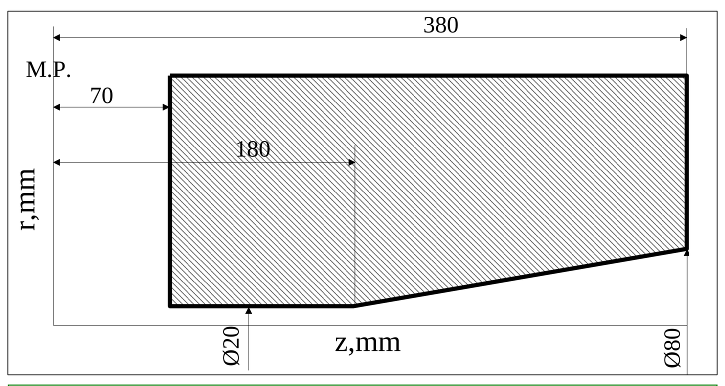

Figure 5:Magnetic plug scheme

SPIRAL INFLECTOR I

The spiral inflector I rotates the beam onto the median plane of the cyclotron. In the case of harmonic number h = 2, the inflector of DC72 cyclotron with magnetic radius of 28.7 mm is used. The ECR extraction voltage Uinj varies from 15.69 kV to 17.27 kV for ions having A/Z in the range 5.0 ($^{40}Ar^{8+}$) ÷ 5.5 ($^{209}Bi^{38+}$).

In the case h = 3 the new inflector with magnetic radius ρ_M = 32.0 mm is used. Then the voltage Uinj varies from 13.14 kV to 14.31 kV in the case of injection of ions having A/Z in the range from 7.577 ($^{197}Au^{26+}$) to 8.25 ($^{132}Xe^{16+}$).

SINUSOIDAL BUNCHER IBN

To improve the efficiency of beam capture into the ac-celeration a sinusoidal (one harmonic) buncher IBN, located outside the yoke of the magnet at a distance of 2.493 m from the median plane of the cyclotron, is used. The maximum applied voltage at the grids of buncher is 423.4 V for the injecting ions having A/Z = 5.5 ($^{209}Bi^{38+}$). The efficiency of bunching is approximately equal to 2 (see Fig.6) for all types of ion to be used.

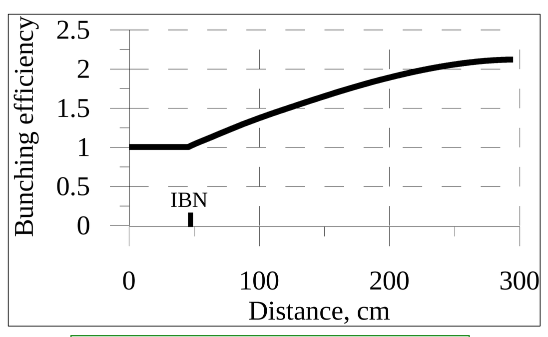

Figure 6a: Bunching efficiency. $^{209}Bi^{38+}$ beam transport, h = 2

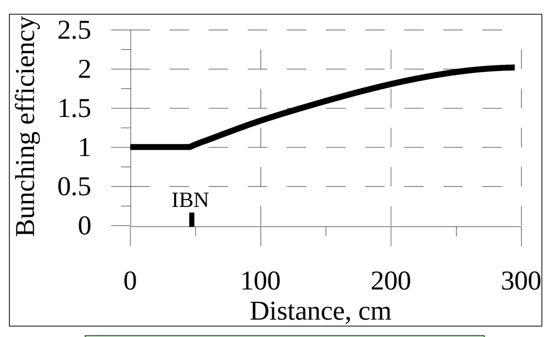

Figure 6b: Bunching efficiency. $^{132}Xe^{16+}$ beam transport, h = 3

SIMULATION RESULTS

The calculations of ion injection with the parameters specified in Table 3 were carried out. In all cases, the transfer efficiency is equal to 100%.

A/Z=5.5, B_0=1.546 T, ρM=28.7 mm, h=2

Transport of 209Bi38+ ion beam was considered. In this case the magnetic field at the center of the cyclotron B_0 = 1.546 T is maximal. The results of simulation of $^{209}Bi^{38+}$ ion beam transport are shown in Fig.7-10.

Figure 7 shows trajectories of $^{209}Bi^{38+}$ ions in the axial injection beam line.

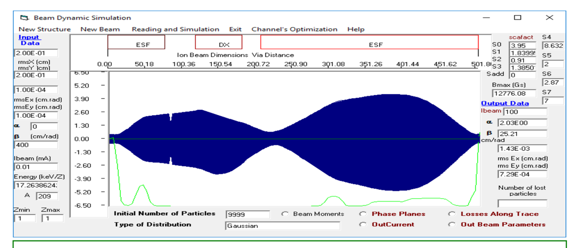

Figure 7: $^{209}Bi^{38+}$ ions trajectories.

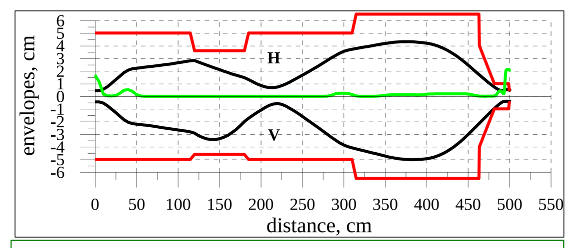

Figure 8:$^{209}Bi^{38+}$ ion beam envelopes.

The horizontal (H) and vertical (V) envelopes of $^{209}Bi^{38+}$ ions in the beam line is shown in Fig.8. The beam envelopes in vicinity of magnetic plug and inflector are presents in Fig.9. The dependence on distance along the beam line of the beam emittance is shown in Fig.10.

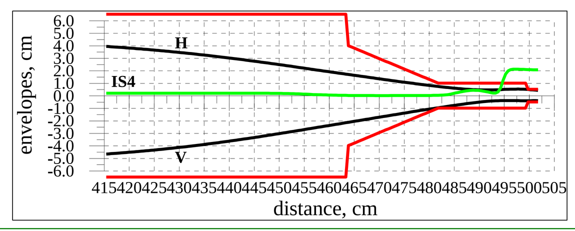

Figure 9:$^{209}Bi^{38+}$ ion beam envelopes near inflector

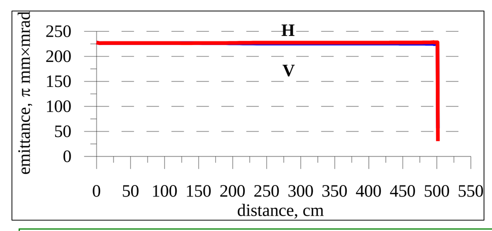

Figure 10:$^{209}Bi^{38+}$ ion beam emittances.

A/Z=8.25, B_0=1.546 T, ρ_M =32.0 mm, h=3

Transport of $^{132}Xe^{16+}$ ion beam was considered. In this case the magnetic field at the center of the cyclotron B_0 = 1.546 T. Fig.11 shows trajectories of $^{132}Xe^{16+}$ ions. The horizontal (H) and vertical (V) envelopes of $^{132}Xe^{16+}$ ions in the beam line is shown in Fig.12,13. Changing of the emittance in the beam line is shown in Fig.14.

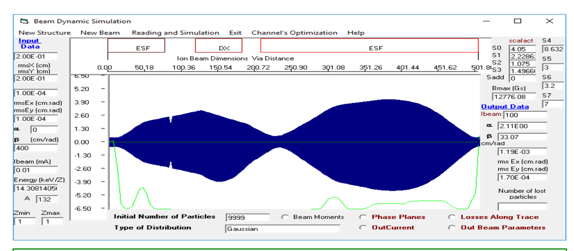

Figure 11: $^{132}Xe^{16+}$ ions trajectories.

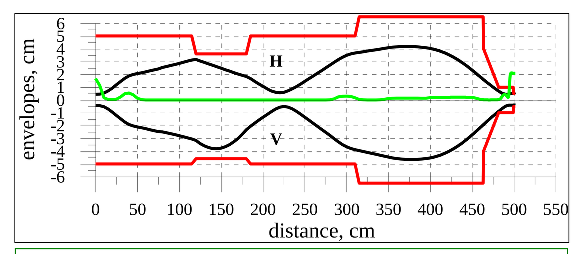

Figure 12:$^{132}Xe^{16+}$ ion beam envelopes.

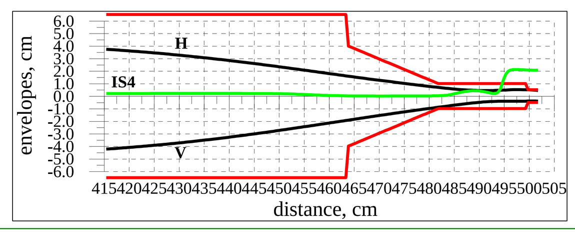

Figure 13:$^{132}Xe^{16+}$ ion beam envelopes near inflector

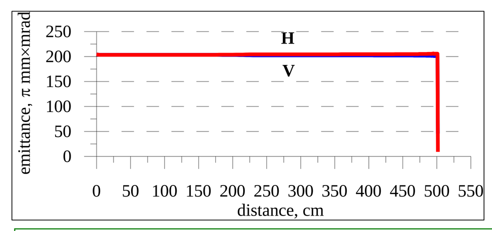

Figure 14:$^{209}Bi^{38+}$ ion beam emittances.

BEAM SPECTRUM ANALYSIS

Two movable diaphragms ID1,2 are used in the beam spectrum analysis. The first diaphragm ID1, has the form of a square with a side of 10 mm and shown in Fig.15, is located at a distance of 354 mm in front of the IM90 magnet.

Figure 15: Diaphragm ID1

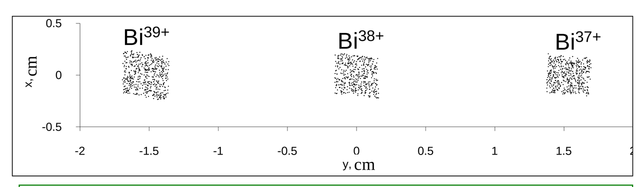

Figure 16: Bi ions distribution at diaphragm ID2

The second one ID2 is a slit with a width of 5 mm <d <10 mm, located at distance of 507 mm after IM90 magnet. The distance between diaphragm ID2 and Faraday cap is equal to 100 mm.

The beam emittance is decreased at diaphragm ID1 in 16 times that give opportunity to separate two neighbor charges in the beam spectrum by means of diaphragm ID2.

The distribution of ions $^{209}Bi^{37+,38+,39+}$ in front of the diaphragm ID2 is shown in Fig.16.

SUMMARY

The axial injection system of DC140 cyclotron allows transporting with of 100% efficiency all ion beams declared in the working diagram of FLNR JINR Irradiation Facility (Fig.1). The proposed system of beam spectrum analysis allows to separate ion charge up to Z=38.

In the calculation the parameters of the existing solenoids IS1-4 of the axial injection channel of the DC-72 cyclotron have been used. The magnitudes of their mag-netic fields are in the design range.

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