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

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Abstract

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research begin the works under reconstruction of the cyclotron U200. The reconstructed cyclotron is intended for acceleration of heavy ions with mass-to-charge ratio *A*/*Z* within interval from 5 to 8 up to energies 2 and 4.5 MeV per unit mass. 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 cyclotron will be used in the microchip SEE testing. The injection into cyclotron will be realized from the external superconducting ECR ion source. The simulation of the axial injection system of the cyclotron is presented in this report.

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 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 4.5 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 numbers *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].

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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 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

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

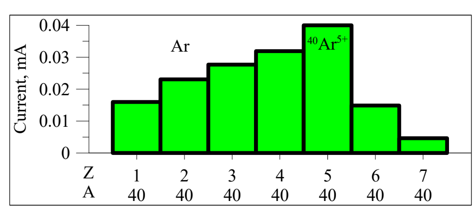

Figure 1: Ar beam current distribution.

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)

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BEAM LINE SCHEME

The scheme of the beam line is shown in Fig. 2.

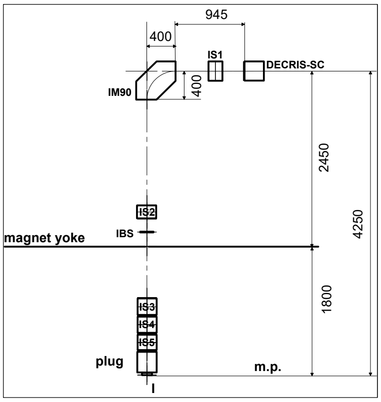

Figure 2: Scheme of the axial injection beam line.

The length of the beam line is equal to 5.423 m. The 90-degree analysing 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

The analyzing magnet IM90 has a bending radius R_M equal to 0.4 m and maximum magnetic field 0.16 T. The existence magnet of IC100 cyclotron axial injection beam line [3] will be used.

SOLENOIDS IS1,2

The solenoids IS1,2 are the part of existing IC100 cyclotron axial injection beam line [3]. Its maximum magnetic field induction 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).

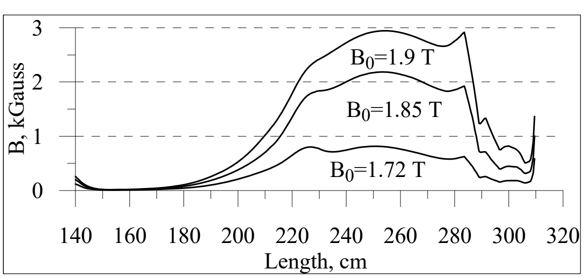

Figure 3: Cyclotron field distribution in beam line.

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.

The scheme of solenoids IS3-5 is presented in Fig. 4. The Table 4 contains the parameters of solenoids. The computer model of the solenoids for the POISSON program code [7] is shown in Fig. 5. Figure 6 gives the on-axis distribution of the magnetic field of solenoids IS3-5.

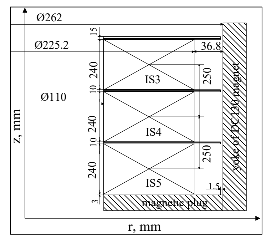

Figure 4: Scheme of solenoids IS3, 4, 5.

Table 4: Solenoids IS3,4,5 Parameters

Maximum induction, kG	3.38
Vacuum tube inner diameter, mm	100
Winding inner diameter, mm	110
Winding outer diameter, мм	225.2
Turn number	150
Winding resistance, Ohm	0.03122
Current, A	450
Voltage, V	14.0
Power supply, kW	6.3

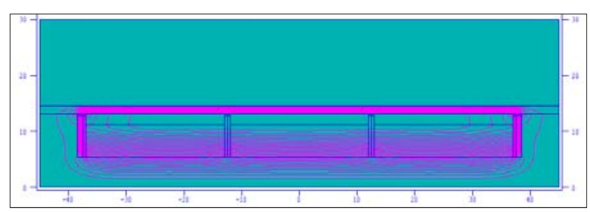

Figure 5: Computer model of solenoids. Dimensions are given in cm.

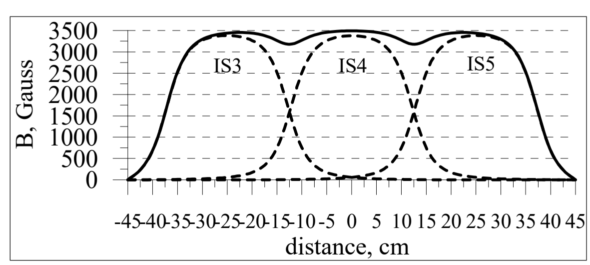

Figure 6: On-axis magnetic field of solenoids.

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MAGNETIC PLUG

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. 7.

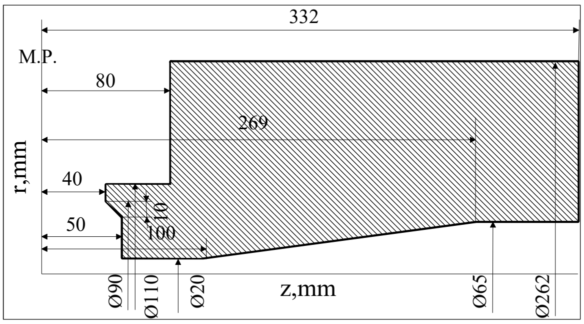

Figure 7: Magnetic plug scheme.

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 is approximately equal to 2 (see Fig. 8).

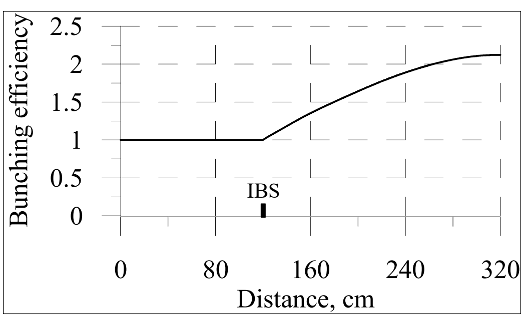

Figure 8: Bunching efficiency.

SPIRAL INFLECTOR I

The magnetic radius of the spiral inflector ρ_M is chosen equal to 2.3 cm. In the case of harmonic number h = 2, for this value of ρ_M, 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.

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, ρ_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).

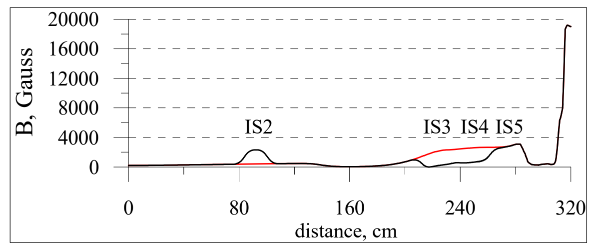

Figure 9: Cyclotron (red line) and total (black line) longitudinal magnetic field in vertical part of beam line. $^{209}Bi^{38+}$ ion beam transport.

The horizontal (H) and vertical (V) envelopes of $^{209}Bi^{38+}$ ions in the beam line is shown in Fig. 10.

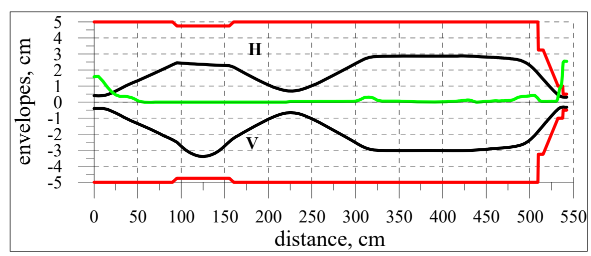

Figure 10: Horizontal (H) and vertical (V) $^{209}Bi^{38+}$ beam envelopes, aperture (red line) and longitudinal magnetic field (green line).

The beam envelopes in vicinity of magnetic plug and inflector are presents in Fig. 11.

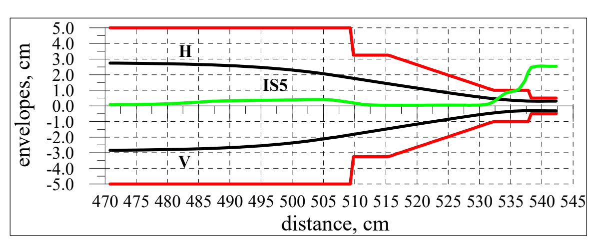

Figure 11: Horizontal (H) and vertical (V) $^{209}Bi^{38+}$ beam envelopes near magnetic plug and inflector.

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The dependence on distance along the beam line of the beam emittance is shown in Fig. 12.

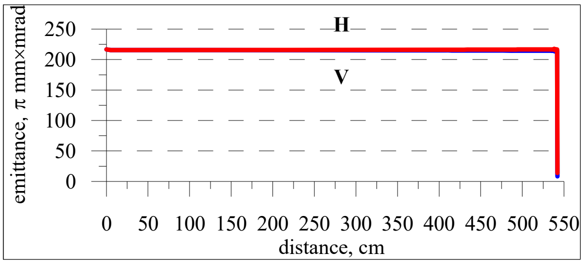

Figure 12: $^{209}Bi^{38+}$ beam emittance.

The bunching efficiency in this case is equal to 2.1 (see Fig. 8)

A/Z=8.0, B₀=1.8445 T, ρ_M *=2.3 cm*

Transport of $^{40}Ar^{5+}$ ion beam was considered. In this case the magnetic field at the center of the cyclotron B_0 = 1.8445 T. In the regime with an intermediate magnitude of magnetic field in the center of the cyclotron, 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). Figure 13 shows the cyclotron field (red line) and the total field of the cyclotron and focusing solenoids (black line).

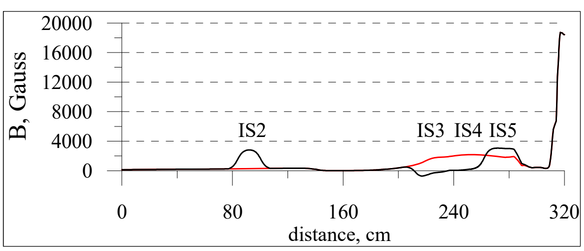

Figure 13: Cyclotron (red line) and total(black line) longitudinal magnetic field in vertical part of beam line. $^{40}Ar^{8+}$ ion beam transport.

The horizontal (H) and vertical (V) envelopes of $^{40}Ar^{5+}$ ions in the beam line is shown in Fig. 14.

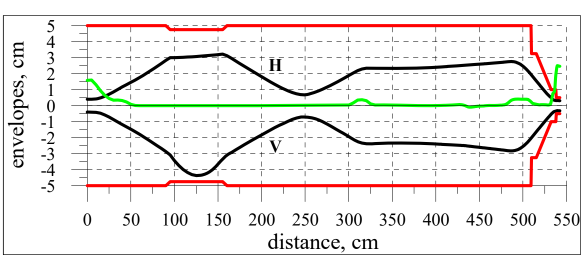

Figure 14: Horizontal (H) and vertical (V) $^{40}Ar^{5+}$ beam envelopes, aperture (red line) and longitudinal magnetic field (green line).

The beam envelopes in vicinity of magnetic plug and inflector are presents in Fig. 15.

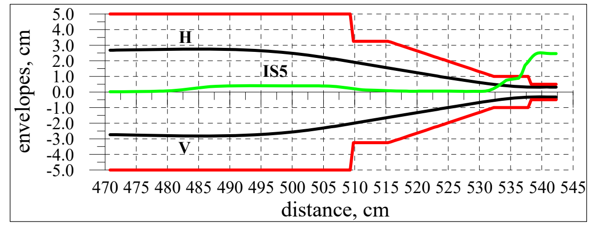

Figure 15: Horizontal (H) and vertical (V) $^{40}Ar^{5+}$ beam envelopes near magnetic plug and inflector.

The dependence on distance along the beam line of the beam emittance is shown in Fig. 16.

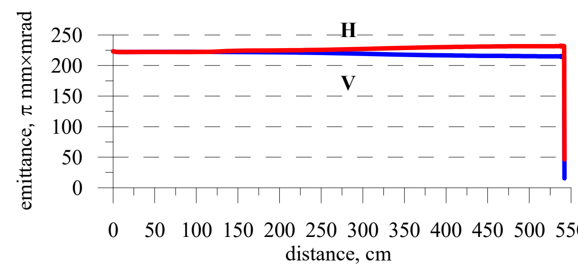

Figure 16: $^{40}Ar^{5+}$ beam emittance.

The bunching efficiency in this case is equal to 1.6 (see Fig. 17). The voltage at the grids is equal to 160 V.

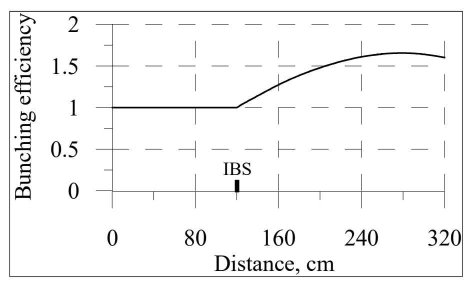

Figure 17: Bunching efficiency. $^{40}Ar^{5+}$ beam transport.

A/Z=8.0, B₀=1.8445 T, ρ_M *=2.9 cm*

Transport of the same ion beam $^{40}Ar^{5+}$ was considered. In this case, the magnetic field at the center of the cyclotron does not change. The magnetic field induction of the compensating solenoids IS3,4 does not change also. The field of solenoids IS2,5 will be greater than in the previous case due to increasing of the extraction voltage U_{inj} up to 17.26 kV (B_{IS2} = 3.211 kG, B_{IS5} = 1.953 kG).

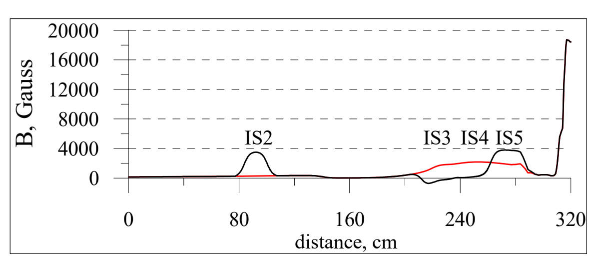

Figure 18: Cyclotron (red line) and total (black line) longitudinal magnetic field in vertical part of beam line. $^{40}Ar^{8+}$ ion beam transport, U_{inj} = 17.26 kV.

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Figure 18 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. 19.

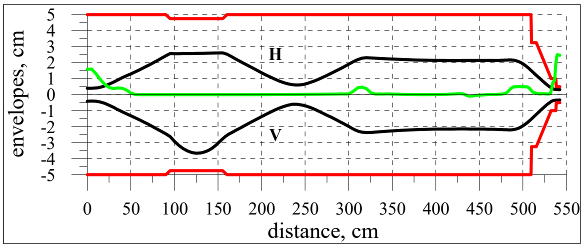

Figure 19: Horizontal (H) and vertical (V) $^{40}Ar^{5+}$ beam envelopes, aperture (red line) and longitudinal magnetic field (green line), U_{inj} = 17.26 kV.

The beam envelopes in vicinity of magnetic plug and inflector are presents in Fig. 20.

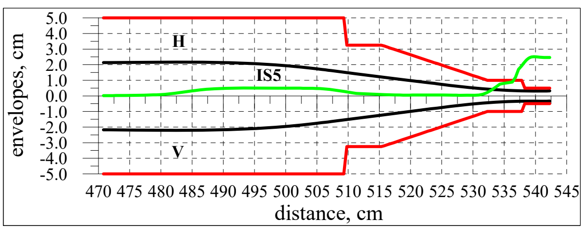

Figure 20: Horizontal (H) and vertical (V) $^{40}Ar^{5+}$ beam envelopes near magnetic plug and inflector, U_{inj} = 17.26 kV.

The dependence on distance along the beam line of the beam emittance is shown in Fig. 21.

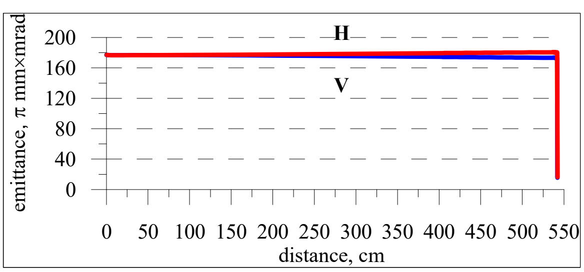

Figure 21: $^{40}Ar^{5+}$ beam emittance, U_{inj} = 17.26 kV.

The bunching efficiency in this case is equal to 1.81 (see Fig. 22). The voltage at the grids is equal to 300 V.

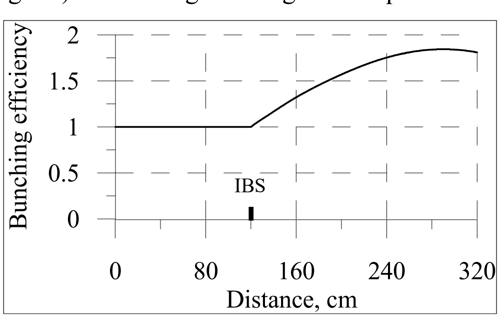

Figure 22: Bunching efficiency. $^{40}Ar^{5+}$ beam transport, U_{inj} = 17.26 kV.

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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