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A STUDY OF CHARGE–EXCHANGE BEAM EXTRACTION FROM THE MULTI–PURPOSE ISOCHRONOUS CYCLOTRON DC–72

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Cyclotrons are frequently used for medical applications together with physics research. In such a case, machine design becomes complicated because the cyclotron must produce beams of different particles at different energies. The beam-extraction is a special problem for these machines. The paper presents a study of the beam extraction from the multi-purpose isochronous cyclotron DC-72 that is being designed and constructed for the Cyclotron Centre of the Slovak Republic (CC SR). Charge-exchange extraction has been studied and optimized. It is demonstrated that extraction of different ions at different energies through a common extraction channel is feasible.

K e y w o r d s: cyclotron, charge-exchange extraction, STRIPEX

1 INTRODUCTION

The Cyclotron Centre of the Slovak Republic (CC SR) has an ambition to run different medical applications together with the physics research [1]. It will be equipped with an isochronous four-sector cyclotron DC-72 that will accelerate ions with mass-to-charge ratio A/q from 1 (H) to 7.2 ($^{129}\mathrm{Xe}^{18+}$) in the energy range from 2.7 MeV/u ($A/q = 7.2$) up to 72 MeV/u ($A/q = 1$), where A is the atomic number, q is the charge-state and MeV/u denotes the kinetic energy per nucleon. The planned main applications and corresponding design beam parameters are listed in Tab. 1. The basic technical parameters of the cyclotron are collected in Tab. 2. The cyclotron is being designed and constructed at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia as a turn-key-ready machine.

Because of the wide application spectrum, the cyclotron will operate in a "light-ion mode" ($A/q = 1$) as well as in a "heavy-ion mode" ($2 < A/q < 7.2$). In this paper, the charge-exchange extraction study for such a multipurpose isochronous cyclotron is presented for the first time. It is demonstrated that charge-exchange extraction of different ions at different energies through a common extraction channel is feasible. The electrostatic extraction option is not excluded, but it has been studied separately.

1.1 Principle of the charge-exchange extraction

The charge-exchange extraction was invented at JINR Dubna [2] and realized for the first time at the 2-meter JINR isochronous cyclotron [3, 4]. Its principle is illustrated in Fig. 1. At the extraction radius, R_k, the particles pass through a stripping foil and increase their charge-state by loosing electrons. Their magnetic rigidity is abruptly changed, which leads to different bending radius of their trajectory. The proper position of the stripping foil must be found in order to direct the stripped ions out of the accelerator into the extraction channel. Positioning of the stripping foil along a well-defined trajectory allows extracting the ions even from different radii, *ie* with different energies. There are several variants of this technique.

Light ions like protons and deuterons are obtained by acceleration of negative ions H^- and D^- that are converted to positive ions by stripping (trajectory #2 in Fig. 1). The charge-state is changed by factor of -1 and the trajectories are bent with the same bending radius but to the opposite direction. In this case, the particles are in fact extracted by inversion of the magnetic rigidity. The efficiency of this technique is close to 100 %.

Heavier ions are accelerated with a positive charge-state q_1 and stripped to a higher charge-state q_2. The magnetic rigidity is reduced by the charge-exchange factor q_2/q_1. In sector cyclotrons, the particle motion after stripping becomes radially unstable due to the action of the first harmonic of the magnetic field. Particles reach the extraction channel either after a single turn in the machine (trajectory #3 in Fig. 1) or after two turns (trajectory #4 in Fig. 1). Exceptionally, more than two turns are used [3, 5]. A spectrum of different charge-states is produced by stripping. However, only one of them follows the trajectory passing through the extraction channel. The efficiency of this technique is therefore ≈ 10–70 %.

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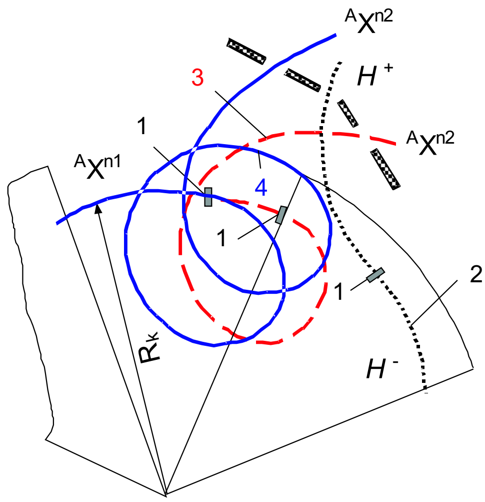

Fig. 1. Principle of the charge-exchange extraction from a cyclotron. 1 = position of the stripping foil, 2 = particle trajectory: negative-to-positive charge-state conversion, 3 = particle trajectory: single-turn extraction, 4 = particle trajectory: two-turns extraction, R_k = extraction radius that defines the energy of the extracted particles.

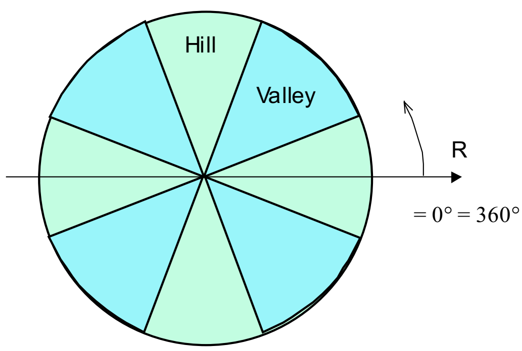

Fig. 2. Definition of the cylindrical co-ordinate system.

In the DC-72 cyclotron, both variants are going to be used, which is the specific feature of this multipurpose cyclotron. Protons and deuterons will be extracted by stripping the negative ions, heavier ions by the single-turn extraction of the positive ions. The latest can also be used for molecular hydrogen ions H_2^+ that are stripped and dissociated into two protons.

2 METHOD OF THE CHARGE–EXCHANGE EXTRACTION STUDY

The main method for studying the extraction was ray-tracing of individual particles passing through the stripping foil. A computer code STRIPEX developed in JINR Dubna has been used for this task [6]. The design goal is to find such a configuration of the extraction system that all particle species over the whole energy-range are extracted through a common extraction channel. This means that central trajectories of all extracted beams should cross at a single common point. The angular differences are compensated for with the aid of a dedicated corrector magnet. Keeping in mind the cyclotron and the experimental hall layouts, this point should be located close to the radius of 280 cm (definition of the cylindrical co-ordinate system is given in Fig. 2).

In order to find a proper angular position of this point (the azimuthal co-ordinate, Θ), an extensive set of simulations was run. In the first step, the central trajectories of different beams were calculated. The input parameters for the STRIPEX include particle attributes (mass number, the charge-state before stripping, the charge-state after stripping, the extraction energy) and the azimuthal position of the stripping foil. The radius of the equilibrium orbit corresponding to the given extraction energy is determined by the STRIPEX and the particle trajectory downstream the stripping foil is calculated. From the particle trajectory data, the azimuthal position of the crossing-point on the 280 cm radius was found. The trajectories were calculated for a set of test particles with different mass-to-charge ratios and various charge-exchange factors. Figures 3 and 4 show the azimuthal position of the crossing-point as a function of the stripping foil position for light and heavy ions, respectively. Analysis of the calculated data showed that suitable position of the crossing-point is at $R = 280$ cm and $\Theta = 237.5°$. This point satisfies the design goal and represents the common crossing-point for all test particles. It has been fixed and used for setting-up the extraction system. As an example, Figure 5 illustrates the central trajectory of 15 MeV/u H_2^+ beam for the above selected crossing-point. Figure 6 shows in one plot extraction trajectories of 72, 50 and 36 MeV/u protons obtained by stripping of H^- ions together with extraction trajectories of all heavy ions under consideration. The extraction trajectories represent the central rays of the extracted beams.

2.1 Magnetic fields

The radius of the equilibrium orbits as well as the extraction trajectories depend on the magnetic structure of the cyclotron. The study was made using several magnetic field distributions obtained by:

- Measurements of the magnetic field distribution on a 1 : 13 model with flat sectors;
- Measurements of the magnetic field distribution on a 1 : 5 model with flat sectors at the current supply of 160 A, 240 A, 320 A, 400 A and 480 A, which corresponds to the magnetic flux density $B_{\text{ext}} = 0.847$–1.569 T on the extraction radius $R_{\text{ext}} = 111.8$ cm.
- Measurements of the magnetic field distribution on a 1 : 5 model with shimmed sectors at the currents of 180 A, 240 A, 300 A, 360 A and 420 A.

Figure 7 shows one quadrant of the magnetic field distribution measured on the 1 : 5 model with shimmed sectors. The plot is produced by “BCALC”-code [7].

The crossing-point has been fixed by calculations based on the field distribution measurements on the

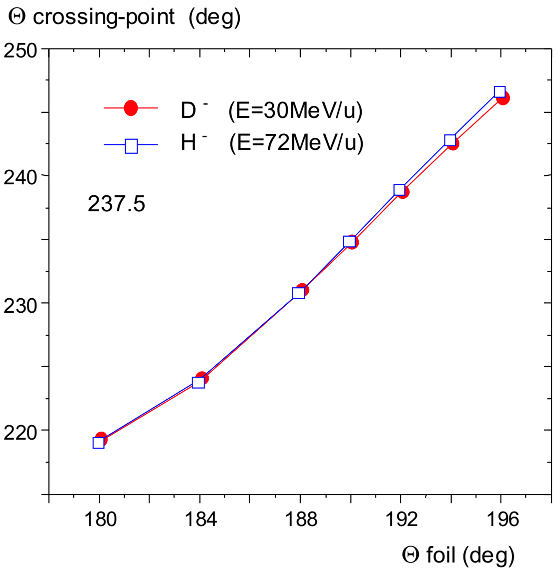

Fig. 3. Azimuthal position of the crossing-point as a function of the azimuthal position of the stripping foil: light ions. The crossing-point is on the radius of 280 cm.

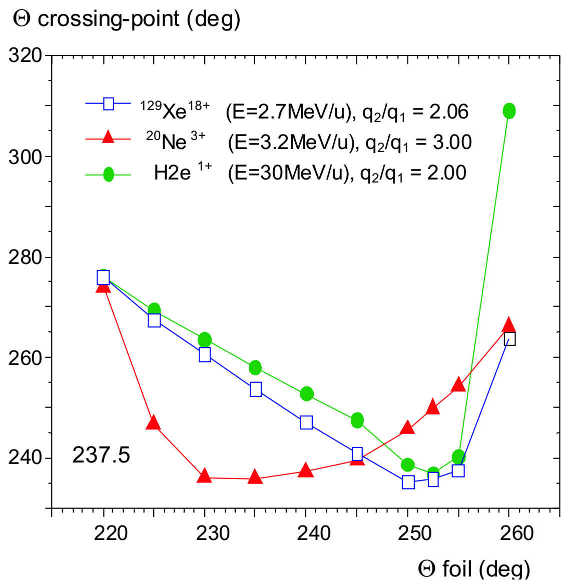

Fig. 4. Azimuthal position of the crossing-point as a function of the azimuthal position of the stripping foil: heavy ions. The crossing-point is on the radius of 280 cm.

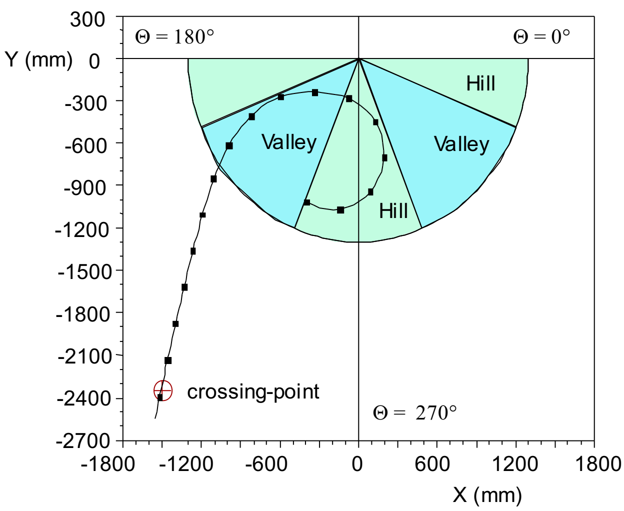

Fig. 5. An example trajectory of a 15 MeV/u H_2^+ ion after stripping and dissociating into two protons.

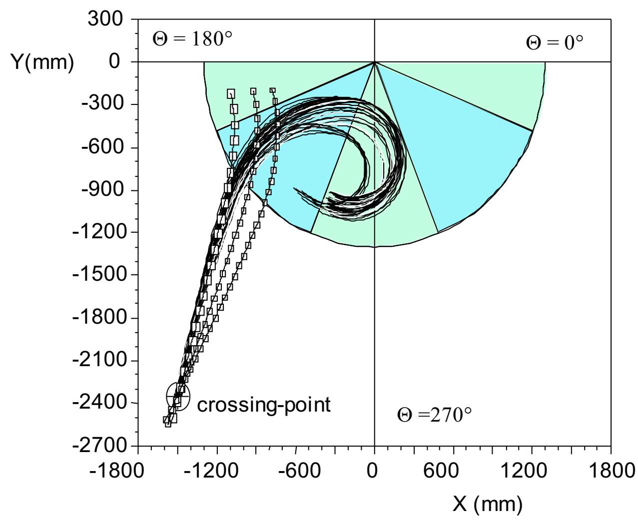

Fig. 6. Extraction trajectories of all ions under consideration.

1 : 13 model. The differences between other field distributions and this reference one are reflected by refinement of the stripping foil position. We have observed that the foil-position region was almost identical for light ions (H^-, D^-) independently of the magnetic field distribution model. It occupies a region of ≅ 10° (187°–197°) azimuthally and ≅ 45 cm ($R = 75$–120 cm) radially. For heavy ions, the stripping-foil region was ≅ 30° (230°–260°), ≅ 20° (235°–255°) and ≅ 15° (240°–255°) for the 1 : 13 model, the 1 : 5 model with flat sectors and the 1 : 5 model with shimmed sectors, respectively. Finally, the region between 235° and 260° has been chosen for technical specification of the machine. The radial span of the foil position is from 100 cm to 115 cm. Resulting regions for the stripping foils are depicted in Fig. 8.

3 BEAM ENVELOPES SIMULATION AND OPTIMIZATION OF THE STRIPPING FOIL POSITION

Having traced the central rays of the extracted beams, another set of calculations has been run to determine the beam envelopes and the beam-size in the crossing-point. The beam emittance immediately before stripping is estimated by analytical formulas describing the particle dynamics in cyclotrons [8–10]. In the vertical plane (perpendicular to the median plane of the cyclotron), the emittance after stripping is assumed to be identical to the emittance before stripping. In the horizontal plane, the beam emittance consists of several “beams” because the stripping foil covers more than one orbit. Similarly, the energy spread is estimated taking into account the contributions from several orbits [11]. Interaction of ions

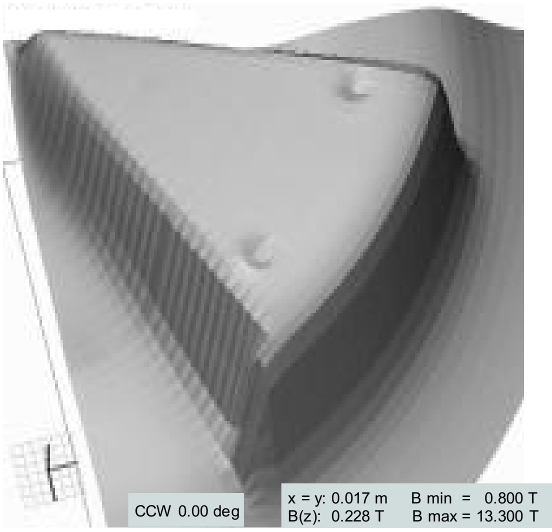

Fig. 7. A 3D-view of the magnetic field distribution as produced by BCALC. One 90° quadrant with a well-pronounced hill is showed.

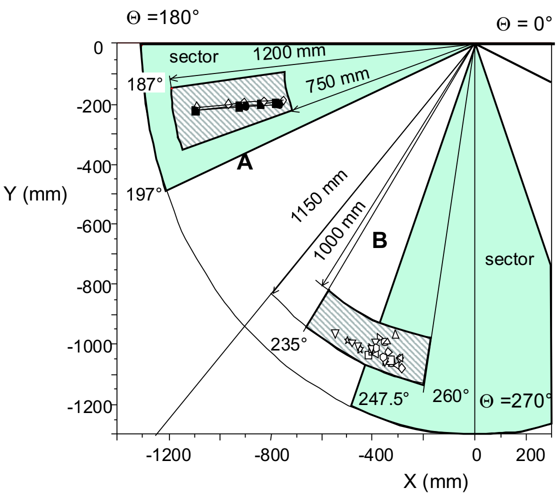

Fig. 8. Regions allocated for the stripping foil. A – extraction of proton and deuteron beams, B – extraction of heavy-ion beams. Inside the regions, exact calculated positions of the stripping foil are depicted.

with the stripping foil for typical foil-materials (*eg* carbon) and thickness (40–60 μg/cm^2) can be neglected.

Since STRIPEX is a ray-tracing code, the sample particles are generated from the expected emittance diagram. Individual trajectories of all sample particles are calculated. The beam-size in the crossing point is obtained by analysis of the STRIPEX output data.

We have observed that the beam-size for heavy ions Li^{1+}, N^{3+}, Ne^{3+}, Ar^{6+} and Kr^{12+} with the charge-exchange factor from 2.1 to 3 in the crossing-point is less than 50 mm in both planes. However, beam-size for ions H_2^{1+}, He^{1+}, Ar^{8+} and Xe^{18+} with the charge-exchange factor close to 2 can be as large as 150 mm in the horizontal plane. This is due to the fact that those ions pass too close to the hill/valley edge (see Fig. 6) that is characterized by a high gradient of the magnetic field. It was necessary to optimize the foil position for those ions. Calculations showed that a possible solution could be to extract those ions from smaller radius at the correspondingly higher magnetic fields. After this optimization, the beam-size in the crossing-point has been reduced down to 80 mm in the horizontal plane.

4 RESULTS

The results are given in Tab. 3 that contains the basic parameters of the extracted beams. The configuration of the extraction system, position of the crossing-point and stripping foil as well as central trajectories of the extracted beams have already been presented in Fig. 6 and 8.

5 DISCUSSION

The goal of the study was to investigate and check the feasibility of extracting different ion beams from multi-purpose cyclotrons. Although the ray-tracing calculations have to be re-done for each particular magnetic field distribution, the results can be used as a conceptual guideline for similar cyclotrons as well. Design of the extraction system involves some other issues like the charge-state distribution of the stripped ions, life-time of the stripping foil, *etc* that will briefly be discussed in this section, too.

5.1 Charge-state distribution and stripping foil life-time

The charge-state of a fast moving ion (projectile) is mainly determined by the balance between electron capture and electron loss. The charge-state distribution has been described in [12] and the works cited therein. In the first approximation, it can be described by the Gaussian probability distribution $f(n_i)$:

$$f(n_i) = \frac{1}{\sqrt{2\pi}\sigma}\exp\Big(-\frac{(n_i-\overline{n})^2}{2\sigma^2}\Big) \tag{1}$$

where n_i is the particular charge-state of interest, $\overline{n}$ is the mean equilibrium charge-state and σ is the standard deviation.

Empirical and semi-empirical formulas for determination of the mean equilibrium charge-state and the standard deviation of the charge-state distribution are given in [12, 13, 14]. The most recent work [12] gives the relation for the equilibrium charge-state $\overline{n}$ based on a multi-parameter least-squares fit of experimental data points:

$$\overline{n} = Z_p\frac{12x + x^4}{0.07x^{-1} + 6 + 0.3x^{0.5} + 10.37x + x^4} \tag{2}$$

Table 1. The planned main applications and corresponding beam parameters of the DC-72 cyclotron.

Application	Particle species	Energy (MeV/u)	Intensity (eμA)
^{123}I production	proton	30	50
^{87}Rb production	proton	30	30
^{67}Ga, ^{201}Tl, ^{111}In production	proton	30	100
Proton therapy	proton	72	0.05
Fast neutron therapy	proton	66–72	30–35
Applied research	Li – Xe	2.8–2.7	5–1
Mass-spectrometry	C – Kr	8.6–2.8	20–2
Physics research	Li – Xe	2.8–2.7	5–1

Table 2. The basic technical parameters of the DC-72 cyclotron.

Pole diameter	2.6 m
Number of sectors	4
Number of Dees	2
Sector angle	45°
Dee angle	42°
Extraction radius	1.118 m
Average magnetic field on the extraction radius	1.12–1.51 T
Magnetic field in the central region	0.904–1.505 T
Gap between poles (valley gap)	275 mm
Gap between sectors (hill gap)	60 mm
Maximum Dee voltage	60 kV
Frequency range	18.5–32 MHz
Harmonic numbers	2, 3, 4, 5, 6
Light-ion source (H^-, D^-, H_2^+)	Multicusp
Heavy-ion source	ECR
Injection	Axial, spiral inflector
Beam emittance on target	$< 20\pi$ mm mrad

where

$$x = \Big(\frac{yZ_p^{-0.52}Z_t^{-0.019Z_p^{-0.52}y}}{1.68}\Big)^{1+\frac{1.8}{Z_p}} \tag{3}$$

Z_p and Z_t are the atomic numbers of the projectile and target atoms, respectively, y is the projectile velocity divided by the Bohr velocity of 2.19×10^6 m/s.

The standard deviation of the mean equilibrium charge-state probability distribution is a complicated function of many parameters. Empirical formulas are given in [14].

The stripping media can be gas or solid targets. A 40–60 μg/cm^2 carbon stripping foil is going to be used at DC-72 cyclotron.

From the machine operation point of view, the foil life-time is an important parameter. It can roughly be estimated [15]:

$$T \cong 6000\frac{E_{\text{ext}}}{JZ_p^2} \tag{4}$$

where T is the foil life-time in hours, E_{ext} is the particle energy in MeV/u, Z_p is the particle atomic number and J is the particle-current density in particle-μA/cm^2.

In the DC-72 cyclotron, the expected foil life-time is about 400 to 4000 hours for protons and 10 to 400 hours for heavy ions depending on beam energy, intensity and the particle species.

5.2 Deflector option and a corrector magnet

Another possibility to extract ions from a cyclotron is an electrostatic deflector that "kicks" particles out of the stable orbits and directs them into the extraction channel. This option has not been definitely dropped for the DC-72 cyclotron and is currently under study. Combining both extraction methods in the single machine is an issue, but it would probably be difficult. A main advantage of the electrostatic deflector is a higher extraction efficiency for heavy ions, because converting the accelerated ions into a spectrum of charge-states is avoided in this case. On the other hand, the efficiency for protons and deuterons is lower, typically less than 70 %. It is therefore less attractive from the point of view of the machine activation and radiation protection. Only one electrostatic deflector can be installed in the machine. In contrast to this, two identical charge-exchange extraction systems can be installed on the opposite sides of the cyclotron. It means that the beams can be extracted in two opposite directions. This feature is going to be used at the DC-72 cyclotron.

The results of the present study contain also important input data for design of the corrector magnet that is used to compensate for angular spread of different beams in the crossing-point. These angles are from 9° to 28° with respect to the sector axis $\Theta = 270°$ (see Fig. 6).

6 CONCLUSIONS

Feasibility of extracting different ion beams from multi-purpose isochronous cyclotrons by the charge-exchange extraction has been demonstrated. The methodology as well as the layout of the extraction system developed for the DC-72 can be applied for similar cyclotrons, as well. The spectrum of extracted ion species and energies is large and the presented design of the extraction system is rather unique. The results represent a reasonable starting point for the final optimization of the extraction system, which is going to be launched after getting data on actual magnetic field distribution. This data will be obtained from measurements on the real DC-72 magnet, which are scheduled by the end of 2003.

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Table 3. The parameters of the extracted beams from the DC-72 cyclotron. A/q = mass-to-charge ratio, q_2/q_1 = charge-exchange factor, E = extraction energy, η = extraction efficiency, X = beam half-width in the horizontal plane, XP = beam divergence in the horizontal plane, Z = beam half-width in the vertical plane, ZP = beam divergence in the vertical plane. The beam parameters are given in the crossing-point.

Ion	A/q	q_2/q_1	E (MeV/u)	η (%)	X (mm)	XP (mrad)	Z (mm)	ZP (mrad)
H^{1+}	1	−1	36–72	≅ 100	10–30	5–10	6	2–3.5
D^{1+}	2	−1	15–30	≅ 100	10–30	5–10	7	2–3
H_2^{1+}	2	2	15–30	≅ 100	40	15–30	25	7.5–9
$^3He^{1+}$	3	2	7–14	≅ 100	40	25–40	25	8–10
$^4He^{1+}$	4	2	4.3–8.6	≅ 100	40	30–40	25	7–11
$^{14}N^{3+}$	4.667	2.333	3.1–6.2	70–88	20–30	10–15	5–10	3–5
$^{40}Ar^{8+}$	5	2–2.125	2.8–5.6	15–40	25–40	10–40	5–40	3–12
$^{40}Ar^{6+}$	6.667	2.33–2.5	2.5–3.2	35–40	20–30	10	5	3
$^{20}Ne^{3+}$	6.667	3	2.5–3.2	65–85	22	12	5–15	3
$^7Li^{1+}$	7	3	2.5–2.8	≅ 100	20–25	12	6	3
$^{84}Kr^{12+}$	7	3	2.5–2.8	25	15–30	10	5–10	2–4
$^{129}Xe^{18+}$	7.167	2–2.06	2.5–2.7	10	10–40	10–25	15–50	10

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