ACCELERATION OF LOW-CHARGE KRYPTON IONS IN THE CYTRACK CYCLOTRON

Yu. N. Denisov, G. A. Karamysheva, O. V. Karamyshev
Joint Institute for Nuclear Research, Dubna, Russia

Abstract

The basic results of numeric simulations of krypton ion motion with decreased charge in the CYTRACK cyclotron are presented. CYTRACK is the world's first industrial cyclotron dedicated to the production of track membranes. Computer modeling confirms the possibility of ion acceleration in the magnetic field with an increase in the level of the magnetic field by 1.6% on the 6 harmonic of the accelerating system. The beam energy will be sufficient for the exposure of a film with a thickness of 10 μm.

INTRODUCTION

The CYTRACK cyclotron [1], designed to irradiate polymer films used in the production of separating and filter elements for medical, industrial, and domestic purposes, was devised and manufactured at the Joint Institute for Nuclear Research. This cyclotron is intended for the acceleration of heavy ions with $A/Z \approx 5$ up to the energy 2.4 MeV/nucleon.

CYTRACK was commissioned in August 2002: a beam of Ar_{40}^{+8} ions was accelerated and ejected [2,3]. The world's first industrial cyclotron for track membrane production has become the basic facility of NPK ALFA, which manufactures medical equipment for membrane plasmapheresis. Nowadays NPK ALFA is a unique research and production complex that stock produces track membranes (with a pore diameter of 400 nm) as well as medical apparatus for plasmapheresis. The track membrane is a polymer film made of lavsan (polyethylene terephthalate) or polycarbonate 10 to 25 μm thick in which there is a system of through pores.

To improve the quality of the membranes to extend the field of application, it is necessary to irradiate a film with heavier ions, especially with accelerated krypton ions. The currently operating ECR source does not produce krypton of the needed charge size. In this paper we analyze the possibility of accelerating krypton ions with a charge below the design one, namely 11+ and 12+.

CYTRACK PARAMETERS

The CYTRACK accelerator is an isochronous cyclotron with an azimuthal variation of magnetic field (a four sector structure), an axial ion injection, a high frequency accelerating system, and an electrostatic ejection system. The main specifications of the CYTRACK cyclotron are presented in Table 1. The general view of the accelerator is shown in Fig. 1.

Table 1: Cyclotron parameters

Accelerated ions	Ar_{40}^{+8}
Initial energy, MeV/nucleon	0.003
Final energy, MeV/nucleon	2.4
Final acceleration radius, mm	730
Operating vacuum, Torr	3×10^{-7}
Magnet overall dimension, m^3	3.7 × 2 × 1.65
Magnetic field level, T	1.48
Dees voltage, kV	40
Resonant frequency, MHz	18.25
Acceleration ratio	4

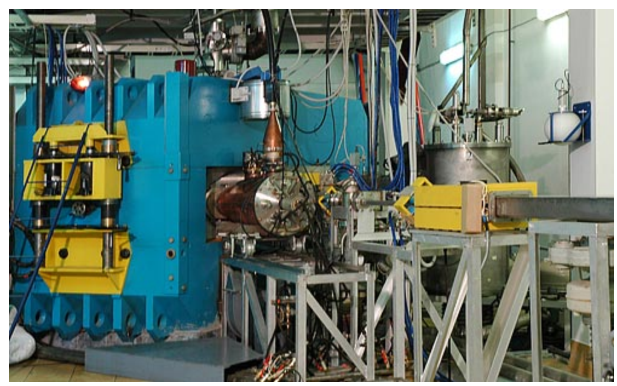

Figure 1: General view of the accelerator.

The ECR type ion source produces 3 keV/nucleon ions; the intensity of an argon beam on the Faraday cup placed in the diagnostic unit at the beginning of the injection line is on the order of 10 μA. The injection system incorporates a buncher. It also includes an ion guide, an analyzing and a turning two section magnet, and beam focusing and adjustment elements.

A spiral electrostatic inflector is used to turn the ion beam from the vertical to the horizontal plane of the CYTRACK cyclotron. A device is designed that allows the inflector to rotate around its axis (±8°) to adjust the ion trajectory to the starting radius and starting angle in order to optimize the initial conditions for ion acceleration in the cyclotron. The ions are injected into the cyclotron's chamber at a radius of 5.3 cm.

A radio-frequency accelerating system tuned to a fixed frequency is used to accelerate ions in the cyclotron's magnetic field. The RF system consists of two quarter wave resonators with accelerating electrodes in the form of dees. The RF resonators assure a frequency range from 18.250 to 18.600 MHz. The two dees of the accelerating system have an azimuthal extent of 45° and are located in the opposite valleys of the magnetic system.

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KRYPTON ION ACCELERATION IN THE CYTRACK CYCLOTRON

Our aim is to accelerate krypton ions of lower charge at a generator frequency identical to that for the acceleration of argon ions with *A*/*Z* = 5, namely at 18.25 MHz. Without changing the RF system frequency, the lower charge ions will be accelerated at a higher harmonic of the RF system. Recall that the design ions are accelerated at the fourth harmonic. Let us first decide on the charge of the accelerated ion and hence on the corresponding acceleration multiplicity. Of practical use will be krypton ions of energy no less than 1 MeV/nucleon. Upon the acceleration of ions of krypton 8+ or 9+ on the 8 harmonic of the RF system, the final energy will be around 0.6MeV/nucleon, which is obviously inadequate. Therefore, we have restricted ourselves to an analysis of the possibility of accelerating krypton ions on an accelerating field harmonic that is not over 6. For such an acceleration regime, the krypton ions with charge 11+ and 12+ will have the closest revolution frequency in the produced magnetic field of the cyclotron, so they were chosen for the calculations presented below.

The acceleration of ions with a charge distinct from the design one involves a number of problems. First, ions with nondesigned *A*/*Z* are injected onto a different starting position; therefore, for the beam to be positioned onto the equilibrium accelerated orbit, it is necessary first and foremost to decrease the ion injection energy.

Second, in our case it is impossible to accelerate ions only at the expense of a multiple change in frequency; the level of the magnetic field should be changed in addition. A strong change in the magnetic field level may lead to a disruption of the formed isochronous increase of the average field.

Third, the dependence of the average magnetic field along the cyclotron radius is formed to match the ion with specified *A*/*Z*, i.e., the change in the dependence of the average field along the radius must correspond to the change in the ion charge. The missing correcting magnetic coils in the CYTRACK cyclotron constrain the acceleration of ions with nondesigned *A*/*Z* values.

An exact model of the cyclotron center (including the inflector, the inflector's housing, and the accelerating electrodes (see Fig. 2)) was made to analyze the possibility of accelerating krypton ions of lower charge.

The starting coordinates of the beam can be changed over a certain range by turning the inflector; in doing so their incomplete correspondence with the starting coordinates of the equilibrium accelerated orbit may be compensated for by changing the amplitude of the accelerating voltage on the dees. In Fig. 3 the solid and dashed and dotted lines correspond to the ion trajectories for two positions of the inflector; the accelerating voltage amplitude is chosen so that the orbit is centered as well as possible. The solid line corresponds to the trajectory of a particle at an accelerating voltage of 41 kV; the dashed–dotted line corresponds to the particle trajectory at an accelerating voltage of 60 kV.

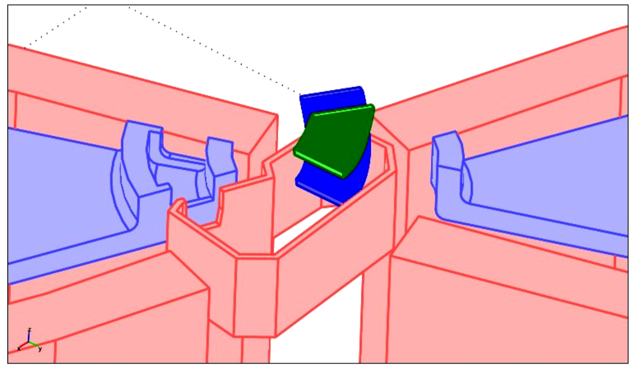

Figure 2: The CYTRACK cyclotron center model.

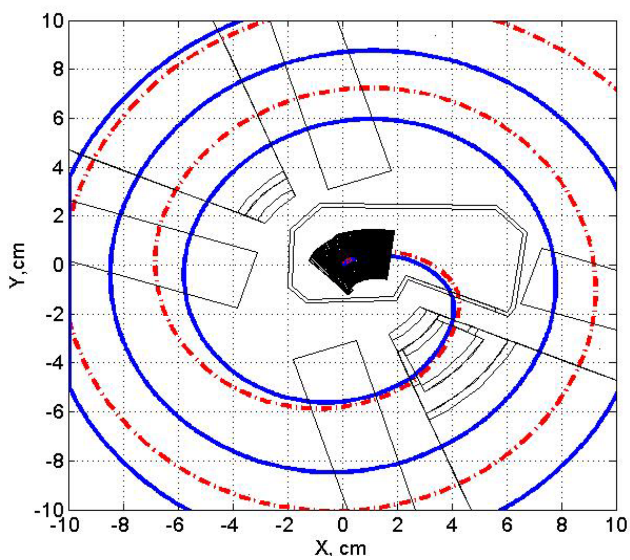

Figure 3: Trajectories of the central particle in the CYTRACK cyclotron center for different positions of the inflector.

The calculations of the cyclotron center showed that it is necessary to decrease the beam injection energy and then accurately position the beam onto the equilibrium well centered accelerated orbit by turning the inflector and changing the amplitude of accelerating voltage.

Acceleration of Kr_{84}^{+11} Ions

The acceleration of Kr_{84}^{+11} on the 6 harmonic of the accelerating field will require a minimum change in the level of the magnetic field; the beam energy in this case will be the 1.04 MeV/nucleon.

The motion of krypton ions in the magnetic field formed in the cyclotron from injection to extraction was simulated. Calculations showed that the average magnetic field should be increased by a factor of 1.016 to accelerate ions in the cyclotron field with no change of frequency. On the left of Fig. 4, the dashed line shows the energy of the central krypton ion as a function of the number of turns in the cyclotron.

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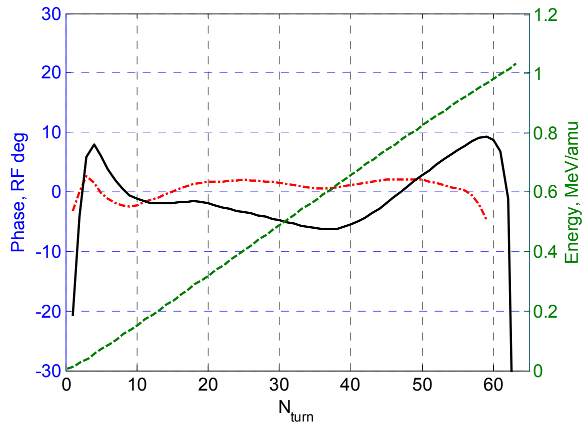

Figure 4: On the right, the phase motion of the equilibrium Kr_{84}^{+11} ion is show as a solid line; Ar_{40}^{+8} is a dashed–dotted line. The dependence of the equilibrium Kr_{84}^{+11} ion energy on the number of turn (dashed line) is shown on the left.

The phase ion drift (the change in the difference value of the ion phase and the phase of the RF system averaged over four accelerating gaps) may be taken as a criterion of correspondence between the formed cyclotron field and the isochronous one. From the right part of Fig. 4, it is seen that the phase drift of the equilibrium ion during acceleration is less than ±10° RF (solid curve), which is allowed. For comparison, the dashed and dotted line shows the phase motion of the central argon ion with A/Z = 5 during acceleration. It is clear that the drift of the argon ion phase is below ±5° RF.

Thus, the field formed in the CYTRACK cyclotron ensures a fixed equilibrium phase of the particle during the acceleration of ions with drift less than ±10° RF; i.e., the isochronism of the formed field is adequate for the acceleration of ions.

The accurate parameters of this and other modes of krypton ion acceleration are listed in Table 2.

Table 2: Acceleration parameters

Accelerated ion	Kr_{84}^{+12}	Kr_{84}^{+12}	Kr_{84}^{+11}
Injection energy, keV*Z	11	11	10
Final energy, MeV/nucleon	1.04	1.26	1.04
Inflector electrodes voltage, kV	5.5	5.5	5
RF_generator frequency, MHz	18.25	18.25	18.25
Acceleration ratio	6	5	6
Voltage amplitude of accelerating field, kV	41	40	45
Average field level	B0 * 0.9315	B0 * 1.118	B0 * 1.016

Acceleration of Kr_{84}^{+12} Ions

Calculations showed that, in accelerating Kr_{84}^{+12} ions on the 6 harmonic, one has to change the magnetic field level by a factor of 0.9315. The decrease in the current in the magnet winding will lead not only to a 7% reduction in the average field level, but also to some decrease in the growth of the isochronous field along the radius, which will serve to decrease the beam phase drift in the extraction area.

To accelerate Kr_{84}^{+12} on the 5 harmonic with no change in the working frequency of the generator, the average field should be increased by a factor of 1.118.

Such an acceleration mode will require a phase shift between the dees of 180°. The increased level of the magnetic field will increase the growth of the average field along the radius, worsening the beam phase motion, which in its turn calls into question the feasibility of this version. The advantage of this mode over the preceding one is the slightly larger final beam energy, 1.26 MeV/nucleon versus 1.04 MeV/nucleon.

CONCLUSION

A computer model of the CYTRACK cyclotron center has been made. The possibility of accelerating krypton ions of lower charge has been studied in the proposed model. Based on the results of an analysis of the krypton ion dynamics in the CYTRACK cyclotron, the acceleration of ions may be recommended owing to a minimum change in the magnetic field level (a 1.6% increase). It is also possible to accelerate ions on the 6 harmonic of the accelerating field with the average magnetic field decreased by 6.8%. In both cases the final energy will be 1.04 MeV/nucleon, which is sufficient for the exposure of the film with a thickness of 10 μm.

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