A PROPOSAL OF HEAVY NUCLEI ACCELERATING COMPLEX

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Abstract

A rather small accelerating complex for the increasing of the ion beam energy up to the Coulomb threshold value (6.5 MeV per nucleon) is proposed. The complex consists of two isochronous cyclotrons, an ECR ion source and a storage ring for ion charge-state changing. Rather moderate dimensions, weight and power consumption are obtained by the adapting of a specific scheme usually used with linacs. Being designed for the heavy radioactive nuclei accelerating, this complex is supposed to be included to the large-scale accelerating projects such as Moscow Meson Facility, TRIUMF in Canada and so on. On the other hand, it can be used independently for accelerating heavy and medium stable ions.

1. INTRODUCTION

A number of programs of scientific research in the field of nuclear physics, astrophysics and other applications need as an aim, or as an intermediate stage, particles with the energy of the Coulomb threshold. The linear accelerators as well as the cycling ones are used to solve this problem. An alternative design is proposed, combining the advantages of the both approaches.

A heavy radioactive nuclei accelerating complex on the energy of 6.5 MeV per nucleon is proposed. The complex is based on two isochronous cyclotrons and an ECR ion source. On the one hand, the using of cyclotrons makes it possible to decrease an accelerating voltage and power. On the other hand, the choice of an investigating the fixed energy of the Coulomb threshold allows to accept an accelerating scheme usually dealing with linacs. Due to this decision the dimensions, weight and power consumption of the complex are essentially reduced.

Since the beam extraction energy per nucleon and therefore the particle velocity are chosen to be constant for the different types of ions, it makes it possible to use RF accelerating systems with the fixed frequencies and radial field distribution in the cyclotrons irrespective of the ion types. Therefore there is no need in a complicated system to form the magnetic field, and the magnets with a small air gap can be used.

2. ACCELERATING SCHEME

The accelerating complex to be proposed is a rather independent module. It concerning with heavy and medium stable ion beams as well as heavy radioactive isotopes on the another. In the last case it can be used as a part of the large-scale accelerating project. The accelerating scheme in this case is shown in Figure 1. The border indicates the proposed module itself.

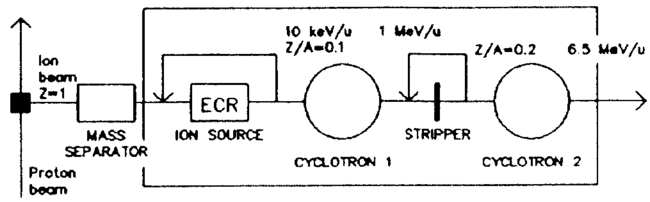

Figure 1. Accelerating scheme

The beam of ions with the charge Z = 1, produced in a target as a result of interaction with a proton beam of high energy after passing through a mass-separator has $\Delta p/p$ = 0.2%. To decrease magnetic rigidity an ECR ion source is used. It is fitted in such a way to get the beam with the energy of 0.01 MeV per nucleon. After that the ion beam is formed into bunches and injected to the first cyclotron. Extraction energy of 1 MeV per nucleon allows to increase the ion charge while passing through a stripper up to a value Z/A = 0.2 - 0.25. After the second cyclotron beam energy equals to 6.5 MeV per nucleon.

The mentioned values of particle energy on the entrance and on the exit of both the cyclotrons must be precisely supported irrespectively on particle types, their mass and charge state. As it has been shown in the introduction, this leads to the reducing of their dimensions, weight and power consumption.

This scheme has another special feature. Since a beam, produced by both the ion source and the stripper, has wide spread of charge state, each of them has a backward line, which returns unused part of the output beam back to their entrance.

The scheme may be slightly modified. The maximum charge which can be reached by using an ECR source corresponds approximately to Z/A = 0.1 for heavy ions. That is why an ECR ion source with the voltage of ~100 kV is needed to obtain the energy required for the injection in the first cyclotron. At present there is no such an ion source, but this question is under investigation. As an alternative variant an ECR source on 20 kV followed by a small cyclotron with the injection energy of 2 keV/n and the extraction energy of 10 keV/n can be suggested.

3. CYCLOTRONS

A proposed accelerating complex includes two isochronous cyclotrons with four straight sector magnets with a uniform magnetic field in the air gap between sectors (see Figure 2). The uniform field distribution is kept for any type of particles on accelerating without respect of their mass and charge. This is provided by fixed energy per nucleon and velocity of particles for any type of ion in any location on the scheme.

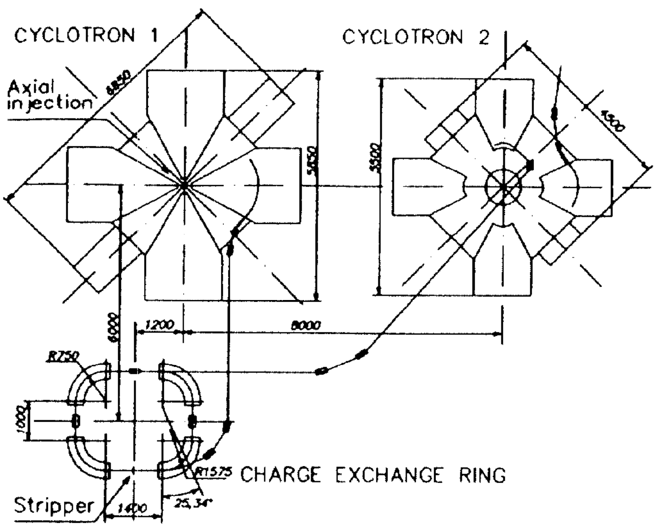

Figure 2. Accelerating complex

Some influence of the relativistic effects on the beam motion is compensated by a slightly curved shape of the magnet edges and (or) by the field correction system intended also for the eliminating of the influence of magnetic saturation effects.

Parameters of both the cyclotrons at the nominal beam rigidity, corresponding to Z/A = 0.1 for the first cyclotron and Z/A = 0.2 for the second are shown in the Table 1. The only values which have to be fitted each time for the different ion types are the magnetic field magnitude and the RF accelerating voltage.

Table 1
Cyclotron parameters

	CYCLOTRON 1	CYCLOTRON 2
SECTOR MAGNETS		
Magnetic field[1], T	1.2	1.5
Air gap, cm	2.5	2.5
Weight, ton	58.0	49.0
Power consumption, A×V	430×80	470×53
RF SYSTEM		
RF harmonic number	8	8
RF frequency, MHz	8.7	26.1
RF voltage[1], V	35.0	150.0
Energy loss[1], kW	11.3	48.0

[1] for Z/A = 0.1 in the first cyclotron and Z/A = 0.2 in the second cyclotron

The parameters of the accelerated ion beam for the emittance values before the first cyclotron of 3π cm·mrad in the radial direction and 10π cm·mrad in the vertical direction and initial momentum deviation $\Delta p/p = \pm 0.2\%$ are shown in the Table 2 and illustrated by the Figures 3 - 5. A little crossing of the neighbor beams on the last orbits of the first cyclotron can be eliminated with more hard requirements to the momentum spread, or by the increasing of the RF voltage.

Table 2
Beam parameters[1]

	CYCLOTRON 1	CYCLOTRON 2
Particle energy, MeV/n	0.01-1.0	1.0-6.5
Orbit curvature radius, cm	12.0-120.3	48.1-122.9
Distance from the center, cm	18.5-184.9	63.3-160.9
Circumference, m	1.27-12.72	4.24-10.76
Betatron frequency:		
in radial direction	1.078-1.079	1.038-1.042
in axial direction	0.734-0.869	0.630-0.633
Beta-function, m:		
β x (on the axis)	0.136-1.359	0.510-1.293
β z (maximum)	0.294-2.552	1.146-2.900
Beam envelope[2], cm:		
x (on the axis)	0.202-0.359	0.202-0.227
z (maximum)	0.542-0.898	0.602-0.757
Dispersion function (on axis), m	0.185-1.845	0.632-1.591
Beam half-width[2,3] in radial direction (on axis), m	0.239-0.728	0.346-0.595
Energy increment per revolution, MeV/n	0.014	0.120
Distance between orbits (on axis), cm	12.9-1.29	3.80-1.47

[1] Two values are given, for the injection and extraction points.

[2] For the next emittance values at the injection point:
3π cm·mrad in radial direction,
10π cm·mrad in axial direction.

[3] For the initial momentum spread $\Delta p/p = \pm 0.2\%$.

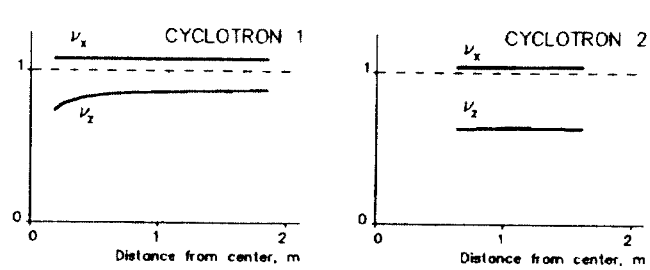

Figure 3. Betatron frequencies.

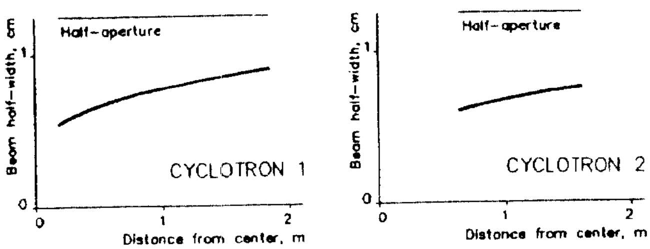

Figure 4. Vertical beam size.

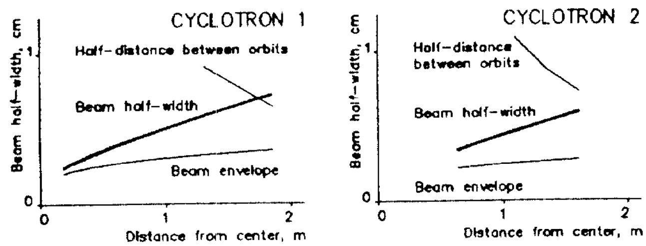

Figure 5. Horizontal beam size.

The construction of both the cyclotrons is almost identical. The only difference is the way of the beam injection into the cyclotrons. The axial injection is used for the first cyclotron. The ion beam is turned to the first orbit with the electrostatic field. The injection into the second cyclotron is provided in the horizontal plane and the bend magnet is used to turn the beam to the first orbit.

The beam extraction is provided by the traditional way. An electrostatic separator followed by the septum magnet are used for the extraction.

The next decisions are accepted to conjugate the cyclotrons: a) RF frequency of the second cyclotron is 3 times greater than the one of the first cyclotron; b) RF frequency in both the cyclotrons is 8 times greater then the particle revolution frequency. As the results of these conditions are the following : 1) the first orbit lengthin the second cyclotron is 3 times less then the last orbit length in the first cyclotron; 2) each bunch from the first cyclotron corresponds precisely to one of the eight RF modes of the second cyclotron. The bunch distribution is shown in Figure 6.

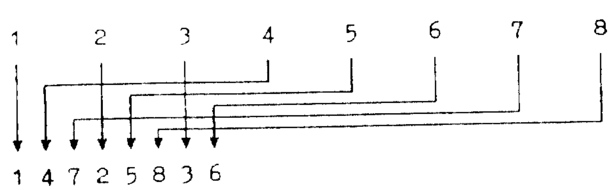

Figure 6. The distribution of the bunches of the first cyclotron in RF modes of the second cyclotron

4. STORAGE RING FOR BEAM CHARGE EXCHANGE

Before the injection into the second cyclotron the ion beam is stripped while passing the foil, which increases the charge of the ions with the energy of 1 MeV per nucleon twice or more. Due to the wide spread of charge states of the resulting beam, the intensity of the part of it with the required charge is significantly reduced. To avoid this loss and to get the beam with the required single charge state a special magnet ring is proposed. It returns the ions with the charge, different from that is chosen for the injection to the second cyclotron, back to the foil. 5 or 6 revolutions are required to transfer about 70% of the beam of heavy ions. 10 revolutions are enough to transfer almost the whole beam. The scheme of the storage ring is shown in Figure 2. The ring consists of four bend magnets with the uniform field and strong focusing at the edges, and two quadrupoles. The target (stripping foil) is located at the center of one of the long drift. The dispersion is absent at that point, so it takes it possible to eliminate emittance growth due to interaction of the ions with the foil. The opposite point on the scheme is occupied by a splitter magnet, which removes the ions with the required charge from the ring in vertical direction. The dispersion here is chosen of such a value to obtain the full splitting of the beams of different charges.

The injection into the storage ring is provided through one of the bend magnets. As the injected ions rigidity is greater than the rigidity of the ions on the orbit, their orbit curvature radius is greater too and the injection can be proposed through the side surface of the magnet.

5. CONCLUSION

The proposal of the complex for accelerating of ions up to the energy of the Coulomb threshold has a set of attractive features. It can be used as a part of the large-scale accelerating projects as well as an independent module for accelerating both the stable particles and the radioactive ones.