Proceedings of the 9th International Conference on Cyclotrons and their Applications
September 1981, Caen, France

ACCELERATION OF THE HIGH-CURRENT BEAMS OF HEAVY IONS UP TO 1-2 GeV/NUCLEON IN THE RING CYCLOTRON

L.A. Sarkisyan

Institute of Nuclear Physics, Moscow State University, Moscow 117234, USSR

Abstract.- The increase in energy of heavy ions (including uranium) from 200-300 to 1000-2000 MeV/nucleon in the ring cyclotron with the passage of the integral radial resonances (Q_r = 2 and 3) is considered. The mean intensity in this relativistic ion factory will be higher approximately by 2-3 order than that in the fast-cycling synchrotron, for the same ion energy at a relatively low vacuum.

At present, several cyclotrons to accelerate ions with the mass number A= 20-60 up to 20--100 MeV/nucleon (2-10 MeV/nucleon for the uranium ions) have been started up or are in the course of assembly [1-4]. A number of cyclotrons to obtain a heavy ion energy of 200-300 MeV/nucleon are being developed [5-9]. The heavy ion energy can be further increased up to 1-2 GeV/nucleon in the cyclotron regime on the basis of the ring cyclotron with the passage of the integral radial resonances Q_r = 2 and 3 [10]. The ring cyclotron with the passage of the integral radial betatron oscillation resonance Q_r= 2,3,4... was proposed to accelerate the intensive proton beams up to several GeV for generating the K-mesons and neutrons [11]. A slow passage of the integral resonances followed by a strong post-resonance decrease (with an increasing energy of the charged particle and oscillation Q_r) of the forced radial amplitude excited in the integral resonance was revealed on the basis of numerical modelling by the complete nonlinear equations of motion. The strong non-linearity of the equations of motion and magnetic field with space variation results in nonlinear shift of free radial oscillations owing to the jump of the forced oscillation amplitude. This limits the distortion of the closed orbit in the integral resonance and permits a slow passage (in terms of energy gain per turn) of the resonance zone. As the nonlinear effects decrease with increasing Q_r, the distortion of the orbit decreases. The free oscillation amplitude is adiabatically damping with an increasing energy of particle [12,13]. The proton ring cyclotrons of the Kaon-factory type have been under development since 1978 in Canada (8.5 GeV, 400 μA) [14] and Switzerland (8 GeV, 100-200 μA)[15]. Consideration is given to a possibility of using the ring cyclotron as a neutron generator at a proton energy of 3 GeV and a mean beam current of 4-5 mA. A possibility of increasing the heavy ion energy attained at the 4-metre cyclotron, up to 250 and, subsequently, 1000 MeV/nucleon by means of a cascade of two ring cyclotrons has been studied, since 1979, at the NRL (JUNR).

Possible parameters of a high-energy high--current ring cyclotron to accelerate heavy ions ($A \leq 60$, A/Z = 2) from 300 up to 1000 MeV/ /nucleon, are given in the table [10]. The uranium ions (A/Z = 2.56) can be accelerated up to an energy of ~ 650 MeV/nucleon. At the cyclotron injection the ion charge increases by nearly one-half due to stripping. The azimuthal extension of spiral sector is ~ 15°; the spiral angle varies by ~ 5° at the period of magnetic field structure. At a tolerance on the second magnetic field harmonic of 0.5 G and an energy gain per turn of 3 MeV per unit charge the increase in the forced radial amplitude of ion in the integral resonance region $Q_r = 2$ (r = 1050 cm, W ≈ 920 MeV/nucleon) is ~ 2 cm . At an ion energy of 1000 MeV/nucleon ($Q_r \approx 2.1$) the forced amplitude will decrease down to ~ 1.5 cm. If the periodicity of magnetic field structure is taken to be 10, the internal (structural) resonance of the 4th-order takes place at a frequency of $Q_r = 2.5$ and is therefore not achieved during the acceleration process. It will be noted that the use of the superconducting windings will permit the radial extent of the ring cyclotron to be reduced in half ($H_o \approx 10$ kG) or the ion energy to be roughly doubled (the periodicity of magnetic field structure is 12). The ion extraction with an efficiency of ≈ 100% can be realized on the basis of the closed-orbit expansion effect [5]. The expected number of ions per second, accelerated in the ring cyclotron, will be 10^{14} for the argon ions and $10^{11} - 10^{12}$ for the uranium ions (at a vacuum of 10^{-7} torr). It should be noted for a comparison that the expected number of ions per second (at an energy of 1 GeV/nucleon) to be accelerated in a fast-cycling synchrotron will be nearly $10^{11} - 10^{9}$ at a vacuum of 10^{-10} torr [16]. At a vacuum of 2.10^{-9} torr the attainable number of ions per second will be still less [17].

The consideration demonstrates the encouraging possibilities of the method of heavy ion acceleration from 200-300 to 1000-2000 MeV/nucleon in the ring cyclotron with the passage of the integral resonances in Q_r since the mean beam intensity is here 2-3 order higher than that attained in a fast-cycling synchrotron for the same ions energy at a relatively low vacuum. A further development of the heavy-ion cyclotron complex will be connected with ion acceleration up to 1-2 GeV/nucleon. Creation of the relativistic ion factories will permit us to study new properties of nuclear matter [18].

References.- 1. Yu.Ts. Oganesyan. Proc. of the VI ALL-Union Conf. on the Charged-Particle Accelerators, Dubna, 1,(1979), 42.
2. C.R. Hoffman et al. IEEE Trans. on Nucl.Sci., NS-22, (1975), 1647.
3. H.G. Blosser, P.A. Johnson, Nucl.Inst. and Meth. 121,(1974), 301.
4. A. Chobert, T.T. Luong, IEEE Trans. on Nucl.Sci., NS-22,(1975),1930.
5. A.A. Vasil'ev et al. Preprint of the JUNR, D9-11584, Dubna, 1978.
6. P. Resmini et al. IEEE Trans. on Nucl. Sci., NS-26(2), (1979), 2078.
7. M. Kondo . IEEE Trans. on Nucl. Sci., NS-26(2) , (1979), 1912.
8. H. Daniel et al. IEEE Trans. on Nucl. Sci., NS-26(3),(1979), 3721.
9. Yu.Ts. Oganesyan. Preprint of the JUNR, P9-12843, Dubna, 1979; G.N. Flerov et al. Abstracts to the VII All-Union Conf. on the Charge-Particle Accelerators, Dubna, D9-637, (1980), 6.
10. L.A. Sarkisyan. Vestnik MGU,21(5)(1980), 95; Abstracts to the VII All-Union Conf. on the Charged-Particle Accelerators,Dubna, D9-80-637, (1980), 10.
11. L.A. Sarkisyan. Proc. of the II All-Union Conf. on the Charged-Particle Accelerators, M., "Nauka", I,(1972), 33; Atomnaya energiya, 30, (1971), 446; 32, (1972), 55.
12. L.A. Sarkisyan. Vestnik MGU, 17(3),(1976), 282; 20(3),(1979), 45; Proc. of the VII All--Union Conf. on the Charged-Particle Accelerators, Dubna, I,(1979), 285; Workshop on Technique of Isochronons cyclotrons, Inst. of Nuclear Physics, Krakow (Poland), Report 1966/PL,(1978), 124.
13. L.A. Sarkisyan. Nucl. Inst. and Meth. 142, (1977), 393; Proceed. of the KAON FACTORY WORKSHOP, Vancouver (Canada), TRI-79-I,(1979) , 203.
14. M.K. Craddock et al. IEEE Trans. on Nucl. Sci., NS-26(2),(1979), 2065; Proc. of the KAON FACTORY WORKSHOP, Vancouver, (Canada), TRI-79-I,(1979),185.
15. W. Joho. IEEE Trans. on Nucl.Sci.,1979 NS-26(2),(1979), 1950; J.P. Blaser. Proc. of the KAON FACTORY WORKSHOP, Vancouver,(Canada),

TRI-79-I,(1979), 202.
16. Y. Hirao. IEEE Trans. on Nucl. Sci. NS-26(3),(1979), 3736.
17. N.I. Venikov et al. Proc. of the V All-Union Conf. on the Charged-Particle Accelerators, M., "Nauka", I,(1977), 88.
18. G.N. Flerov. Proc. of the V All-Union Conf. on the Charged-Particle Accelerators, M., "Nauka", I, (1977),23.

Table

Possible parameters of a high-energy high-current ring cyclotron to accelerate heavy ions (A/Z = 2) up to an energy of 1 GeV/nucleon

Parameter	Value
Injection energy, MeV/nucleon	300
Final energy, GeV/nucleon	1
Magnetic field at the centre, kG	5
Infinite energy radius, cm	1251
Initial radius, cm	810
Final radius, cm	1090
Field-structure periodicity	10
Archimedian spiral parameter, cm	55.6 - 69.4
Field variation	0.6-1
Magnetic field at r_i , kG	6.6
Magnetic field at r_f , kG	10.2
Axial betatron oscillation frequency	0.2
Radial betatron oscillation frequency	1.3-2.1
Number of resonators	5
Energy gain per turn, MeV per unit charge	3
Radio-frequency power, KW	750
Magnet weight, t	8000
Magnet consumption power, MW	1.5
Number of ions per second	10^{14}
Extraction efficiency, %	100