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HIGH-CURRENT DEUTERON CYCLOTRON COMPLEX AS MESON AND NEUTRON GENERATOR FOR ACCELERATOR DRIVEN TRANSMUTATION TECHNOLOGY (ADTT) AND ENERGY PRODUCTION

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INTRODUCTION

An accelerator driven nuclear energy amplifier looks quite attractive compared with a conventional nuclear power plant [1]. In this case the energy of an accelerated beam must be ~1 GeV/nucleon (p,d) and the current in the mA range. An isochronous cyclotron is the best choice for generation of such a beam. A bright example is the PSI cyclotron with beam energy 590 MeV and average beam power ~1 MW [2]. The problem of acceleration of high-intensity particle beams at medium energy in a cyclotron has been studied at the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research (JINR) for many years. On the basis of this research a proposal to construct a high current cyclotron for acceleration of protons up to the energy of 800 MeV has been presented [3]. Progress in studying $dt\mu^-$ - catalysis reactions has opened up new opportunities for practical use of high current beams [4]. That is why we have chosen deuterons to be accelerated in the cyclotron complex. This choice also permits one to decrease the beam current more than twice in comparison with protons at the same energy per nucleon [5]. This will drastically simplify the problem of high-current beam acceleration. The final purpose of the project is to build a Deuteron Cyclotron Complex (DCC) of energy 900 MeV/nucleon with average beam intensity in the milliampere range and as large in size as modern cyclic meson factories. The complex consists of an injector and two superconducting sector cyclotrons DC-I and DC-II of energy 100 MeV and 1800 MeV respectively. The facility could be used for solving a wide variety of scientific and applied problems, the main of which is a driver for the electronuclear energy amplifier.

CHOICE OF PARAMETERS

The main idea underlying the choice of the DCC parameters was to minimize the dimensions and common power consumption at the fixed maximal energy per nucleon. Development of superconducting magnets, progress in decreasing beam losses at acceleration [2] and in designing highly efficient beam extraction systems [6], strong focusing [7] permit both the maximal energy and the maximal intensity of the cyclotrons to be increased. Now, in contract with [8], we have decided to use the same level of the magnetic field (< 5 T) in both cyclotrons DC-I and DC-II. This will permit us to simplify the cryogenic system and to use the results achieved by modeling of the magnet DC-I. A general view of the DCC is shown schematically in Fig. 1.

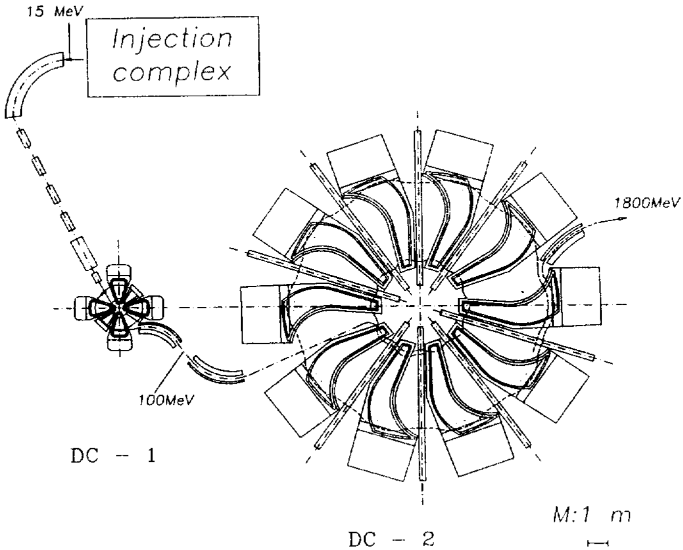

Figure 1. Deuteron Cyclotron Complex (DCC) layout

The main parameters are presented in Table I. The strength of focusing in every element permits acceleration of beams with intensity in the range of 10 mA. We plan to use the orbit expansion effect in order to increase the turn separation on the radii of injection and extraction. In this case, if beam emittances for two neighboring turns are completely separated, the extraction efficiency would reach 100 %. The experimental studies of the possibilities of the strong focusing and effective orbit separation, which were carried out with the electron model of the relativistic isochronous cyclotron [9], have confirmed the reliability of the theoretical calculations [10,11].

TABLE I. Main parameters of DC-I and DC-II cyclotrons

Parameters	DC-1	DC-2
Injection/extraction energy, MeV	15/100	100/1800
Injection/extraction radius, m	0.47/1.11	2.42/6.6
Number of magnet sectors	4	10
Dimensions (R_{max} /height), m	2.5/2.6	9/6
Max spiraling, degrees	0	49
Max/average B-field at R_{in} , T	3.79/1.46	3.8/0.85
Max/average B-field at R_{ex} , T	4.26/1.53	4.0/1.59
Orbital frequency, MHz	12.375	6.187
Harmonic of acceleration	6	12
Number of cavities/gaps per turn	2/4	6/6
Energy gain per turn, MeV	1.0	2.8 ÷ 4.2
Power loss per cavity, kW	60	500

MAGNETS

The magnetic field of the circular cyclotrons can be formed with the help of sector superconducting magnets. The phase and transverse stability of the accelerated beam in DC-I can be achieved with the help of straight sector magnets with convex windings, but in DC-II it is necessary to use spiral magnets. After the first proposal of DCC in 1981 [12] much work has been done on the magnetic system of DC-I [13]. For the DC-I magnets we have chosen the scheme with a cold iron pole and a C-shaped iron yoke. The winding consists of 8 modules. Superconducting NbTi cable $2\times3.5\,mm^2$ in size with critical current 2000 A at 5 T in the form of double pancakes (6 pancakes in a section) is wound directly on a section of the iron pole. The finished sections are put into a double side stainless steel case on both sides and compounded. The modules are divided into two parts (4 in each) for the upper and lower pole, installed in the cryostat and cooled down to the operating temperature. Two-phase helium circulating in the channels of the case will be used for cooling. For fast heating of the winding after the quench the scheme proposed in [14] will be used. The whole winding will shift to the normal state in $t = 0.03$ sec after switching off the power supply, which ensures uniform heating of the winding up to 80 K. The holes of a special shape in the iron pole will be used for shimming the average magnetic field with a precision $\pm\,3\times10^{-3}$ T. At the present time one of four sector of the DC-I magnet has been made. The cryogenic system and the power supply have been assembled and tested. Two modules of the coil have been installed into the cryostat in position on the frame and ready for cooling. The first experimental cooling of the magnet can be made by the end of this year. The interior of the cryostat with two coils is shown in Fig. 2.

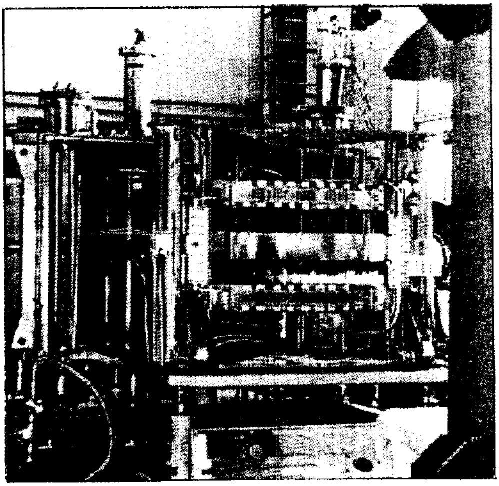

Figure 2. General view of the DC-1 magnet sector

ACCELERATION SYSTEM

The acceleration system of DC-I must produce energy gain of 1 MeV/turn for single charged ions. The radius of injection in this high B-field accelerator is quite small and we have chosen a half-wave resonator with a Δ-shaped accelerating electrode as the best system for the maximal energy gain on the internal and external radii of acceleration. The angle of the Δ-electrode (15°) was determined both by the distance between magnets and by the breakdown voltage in the accelerating gap between the radial edges of the Δ-electrode and the protrusions on the inner sides of the resonator walls. A prototype of the resonator has been designed and constructed [15]. Its photograph is shown in Fig. 3.

Figure 3. General view of the DC-1 accelerator resonator

The resonator is a straight prism with the upper and lower base in the form of an isosceles trapezoid. The azimuthal size of the resonator is 30°. Movable shorts and a trimmer capacitor (which changes the capacity between the external wall of the Δ-electrode and the resonator) can be used both for tuning and for changing the accelerating voltage distribution. The edges of the electrodes of the acceleration gap have a special shape in order to decrease the electric field strength on the surface [16]. In this case $E_{max} / E_{0} = 1.135$, where E_{max} is the maximum field strength on the surface, E_0 is the field in a flat gap. The accelerating voltage distribution has a typical minimum at the radius R=0.6 m. The optimal acceleration system for the cyclotron DC-II is a single gap rectangular resonator with protrusions to form the accelerating field. The experimental data show that the protrusions increase the voltage at the beginning of the acceleration gap in comparison with the sinusoidal voltage distribution [17]. This makes it easier to inject particles into the accelerator.

INJECTION SYSTEM

We have studied three variants of an injector for DC-I: an RFQ-linac and two cyclotrons with a low (CI-1) and a high (CI-2) level of the average magnetic field strength [18÷20]. Our first choice was the RFQ-linac. Its parameters as an injector for DC-I have been described in [8]. The choice of the parameters of the cyclotrons was based on the assumption that the accelerated beam current can be at the level ~10 mA. The main feature of the injector-cyclotrons will be presented now. The magnetic system of the CI-1 consists of four separate radial-sector magnets. This design and a low magnetic field strength ($B \approx 0.5$ T, $B_{max} \approx 1.3$ T) simplify the problem of high current beam injection and extraction. This also permits one to have quite strong axial focusing at all radii. Unfortunately, the dimensions of CI-1 will be as large as DC-I ones. The nearest analog of CI-2 is CYCLON-30 [21]. The diameter and height of CI-2 will be 2 m and 0.8 m respectively. The magnetic field in the hill/valley varies in the limits 1.9÷2.0/0.4÷0.5 T. Such a field can be achieved by 1.5×10^5 ampere-turn per coil. We suppose to design the coil in the superconducting variant. The acceleration system will be of the same type as in DC-I for both cyclotrons. The angles of the Δ-electrodes are 10° and 15° for CI-1 and CI-2 respectively. Some additional characteristics of the injector-cyclotrons are presented in Table II.

TABLE II. Main parameters of CI-1 and CI-2

Parameters	CI-1	CI-2
Injection/extraction energy, MeV	0.3/15	0.3/15
Injection/extraction radius, cm	22/140	8.7/63
Number of magnet sectors	4	4
Dimensions (R_{max} /height), m	2.3/1.6	1.0/0.8
Sector angle, degrees	30	40 ÷ 50
Max/average B-field at R_{m}, T	1.3/0.5	1.9/1.18
Orbital frequency, MHz	4.125	9.281
Harmonic of acceleration	18	8
Number of cavities/gaps per turn	2/4	2/4
Energy gain per turn, MeV	0.4 ÷ 0.8	0.5
Power loss per cavity, kW	60	40

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Аленицкий Ю.Г. и др. E9-96-370

Высокоинтенсивный дейтронный циклотронный комплекс
как мезонный и нейтронный генератор для технологии
трансмутации на основе ускорителя для производства энергии

Приводятся результаты исследований и разработки для дейтронного циклотронного комплекса с конечной энергией ≈ 900 МэВ/нуклон и средней интенсивностью пучка несколько мА. Комплекс состоит из линейного ускорителя (RFQ — linac) и двух секторных сверхпроводящих циклотронов ДЦ-I и ДЦ-II. Обсуждается возможность замены линейного ускорителя циклотроном-инжектором с «теплым» или сверхпроводящим секторным магнитом на энергию дейтронов 15 МэВ. Предложен вариант циклотрона ДЦ-II с 10-секторным сверхпроводящим магнитом и 6 основными и 2 «flat-top» ВЧ-резонаторами. Приводится информация относительно разработки полномасштабного прототипа для нескольких систем циклотрона ДЦ-I.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1996

Alenitsky Ju.G. et al. E9-96-370

High-Current Deuteron Cyclotron Complex as Meson
and Neutron Generator for Accelerator Driven Transmutation
Technology (ADTT) and Energy Production

The research and development results are given for the Deuteron Cyclotron Complex with the final energy about 900 MeV/nucleon and average beam intensity in the milliampere range. The complex consists of a radiofrequency quadrupole linear accelerator (RFQ — linac) and two superconducting sector cyclotrons DC-I and DC-II. The possibility of replacing a linac by a cyclotron injector with the deuteron energy 15 MeV and with «warm» or superconducting sector magnets is discussed. A DC-II version with 10 superconducting sector magnets and 6 main and 2 flat-top radio frequency (RF) resonators is proposed. Information on the constructing of the full-scale prototypes for several DC-I systems is given.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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