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ASYNCHRONOUS CYCLOTRON

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Асинхронный циклотрон

Рассматривается вариант комплекса циклических ускорителей протонов, который может полностью или в основном заменить ядерный реактор в вопросах осуществления трансмутационных технологий в индустриальных масштабах. Для проектирования и создания асинхронного циклотрона отсутствуют принципиальные запреты.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Asynchronous Cyclotron

An idea of a facility based on a cyclic proton accelerator for the transmutation technology on industrial scale is considered. The facility can completely or basically replace nuclear reactors, used for similar purpose. It is shown that there are no principal limitations for designing and constructing an Asynchronous Cyclotron.

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

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Introduction

An idea of a facility based on a cyclic proton accelerator for the transmutation technology on industrial scale is considered. The facility can completely or basically replace nuclear reactors, used for similar purpose.

Since the Manhattan Project time (Los-Alamos, 1942) the charged particle accelerators obviously ranked below nuclear reactors in efficiency of production of military plutonium and tritium, fuel for nuclear power stations, various isotopes etc. However, as time has passed the Accelerator Driven Transmutation Technologies (ADTT) grew more and more attractive, especially in view of increasing number of accidents with nuclear reactors.

Required parameters

We shall briefly consider the requirements to the particle accelerator that could be used in ADTT.

1. High efficiency (of the order of 20÷60 %) for the transformation of the electric power to the beam energy.
2. Acceleration of protons up to energies of 1.0 ÷ 1.5 GeV with a current of 100÷300 mA to be used in an ADTT facility to be competitive with reactors (without additional multiplication of primary neutrons) [1,2].
3. Particle losses during acceleration and transportation should not exceed 0.01 nA/m except injection and ejection regions [7].
4. Operational reliability of the accelerator should be as good as 2000 hours of trouble-free operation.
5. Construction and operational costs of the accelerator should be much less (3÷4 times) than the cost of a reactor of the corresponding power.

The linac projects discussed nowadays in the USA for transmutation technologies, including manufacture of tritium, satisfy basically only the first two requirements. Their construction cost is about $2·10^9$, which is almost equivalent to the cost of a new reactor for the same purposes [1].

However, it seems that the construction of an asynchronous cyclotron, which can basically satisfy all of the above requirements, will allow the cyclic accelerator to outperform not only the nuclear reactor, but also the proton linac of industrial application.

Operational principles of an asynchronous cyclotron

We shall outline the idea of an asynchronous cyclotron [4]. The radius R and the frequency f of the accelerating voltage in a multistage coaxial ring cyclotron (CRC) [5] should be chosen such that the value of the intercavity number of the harmonic q is much more than 10, that is satisfies the following condition:

$$q = \frac{h}{N_c} = \frac{2\pi R f}{N v} >> 10\,,$$

where h is the number of a harmonic of the accelerating voltage on the turn, N_c is the number of cavities in a cyclotron stage, v is the speed of particles. Thus, there is a possibility of limiting the growth of orbit separation, with an opportunity of the unlimited increase in the average radius of the installation. That, in turn, results in the corresponding reduction of the bending magnetic fields and in an increase in the length of field-free intervals, which is important for strong beam focusing.

In other words, the "asynchronous" mode of cyclotron operation, i.e. a significant change in the revolution frequency of particles in one stage by the hopping of the number of the intercavity harmonic q to the nearest values when the beam passes through one sector to another. This effect was provided by modification of a magnetic path in the sectors. This feature would allow the CRC with a corresponding target setup to replace a nuclear reactor. Owing to the above-mentioned CRC property, its name could be changed to Asynchronous Coaxial Ring Cyclotron (ACRC).

ACRC example

We shall consider a two-stage ACRC of energy 1 GeV and current 100÷300 mA as an example. The results of calculations for this facility are summarized in Table 1. The corresponding mathematical model and computer program RAMAD, created at YerPhI[4], were used for simulation.

Table 1

Parameters	**1st stage**	**2nd stage**
E_i - Injected beam energy, MeV	10	370
E_e - Extracted beam energy, MeV	370	1000
n - Number of turns	27	27
R_i - First turn radius, m	100	107
R_e - Extraction radius, m	103.9	110.9
δR - Turn separation, m	0.15±0.001	0.15±0.001
H - Range of fields of magnetic dipoles, T	0.03÷0.35	0.03÷0.35
N_s - Number of sectors	6	6
N_c - Number of cavities	6	6
N_m - Number of magnets in sectors	1	1
δE - Energy gain per sector, MeV	0.8÷3.4	3.4÷4.4
q - Intercavity harmonic number	127÷28	29÷23
f - Frequency of RF-system, MHz	50	50
L_a - Distances from magnet exit to cavity entrance, m	35÷57	36÷58
L_b - Distances from cavity exit to magnet entrance, m	35÷57	36÷58
L_m - Lengths of magnets, m	2÷55	3÷55

Two cyclotron stages are designed, following the scheme of the large-radius separated orbit cyclotron (SOC) [6,7]. Analysis of such a facility shows that an accelerator with large orbits and large field-free intervals is in fact capable of accelerating high-current beams. This has been already demonstrated at HERA, where protons with an average current of 90 mA circulate and where they plan to increase the beam current to 140 mA. The large intensity is ensured by high frequencies of betatron oscillations and, thus by minimization of their amplitudes, by the choice of vacuum chamber with a rather wide aperture, etc. For the same reason, cyclotrons with a small aperture and superconducting bending magnets are less attractive for the acceleration of high-current beams.

Variation in the parameters of the bending magnetic fields, which ensure hops of the harmonic numbers q in the 1st stage, the results of trajectory calculations for a central particle for the first two turns are given in Table 2. In Table 3 the same is shown for the last two turns of the beam.

Table 2

Turn 1										
N_s	q	δE	R	δR	L_a	L_b	L_m	r	H	E
1	127	0.80	100.00	0.00	55.76	55.76	3.57	3.41	0.139	10.80
2	122	0.80	100.00	0.00	52.63	52.63	9.24	8.83	0.055	11.60
3	118	0.80	100.00	0.00	52.25	52.25	9.94	9.50	0.053	12.40
4	115	0.80	100.00	0.00	55.26	55.25	4.48	4.28	0.122	13.20
5	112	0.80	100.00	0.00	56.72	56.72	1.83	1.75	0.309	14.00
6	109	0.80	100.15	0.00	56.17	56.43	2.67	2.55	0.218	14.80
Turn 2										
1	106	0.90	100.15	0.149	56.44	56.44	2.50	2.38	0.24	15.70
2	103	0.90	100.15	0.148	55.48	55.48	4.23	4.04	0.14	16.60
3	100	0.90	100.15	0.148	53.10	53.10	8.53	8.17	0.07	17.50
4	98	0.90	100.15	0.150	55.67	55.67	3.89	3.71	0.16	18.39
5	95	0.90	100.15	0.149	50.79	50.79	12.74	12.17	0.05	19.29
6	93	0.90	100.30	0.150	50.73	50.99	12.69	12.11	0.05	20.19

Table 3

Turn 25										
N_s	q	δE	R	δR	L_a	L_b	L_m	r	H	E
1	29	3.27	103.60	0.150	37.51	37.51	40.44	38.62	0.071	311.98
2	29	3.27	103.60	0.149	39.59	39.59	36.66	35.01	0.079	315.26
3	29	3.27	103.60	0.149	41.65	41.65	32.93	31.44	0.088	318.53
4	29	3.27	103.60	0.150	43.69	43.69	29.23	27.92	0.100	321.81
5	29	3.27	103.60	0.148	45.70	45.70	25.58	24.43	0.115	325.08
6	29	3.27	103.75	0.150	47.14	47.40	22.81	21.78	0.130	328.36
Turn 26										
1	29	3.34	103.75	0.149	48.86	48.86	20.01	19.11	0.149	331.70
2	29	3.34	103.75	0.149	50.85	50.85	16.40	15.66	0.183	335.04
3	29	3.34	103.75	0.149	52.82	52.82	12.83	12.25	0.235	338.38
4	29	3.34	103.75	0.149	54.76	54.76	9.311	8.89	0.326	341.72
5	28	3.34	103.75	0.149	34.61	34.61	45.86	43.79	0.066	345.06
6	28	3.34	103.90	0.150	35.90	36.16	43.37	41.41	0.070	348.40

One can see from the tables that for keeping the required asynchronous condition at the beginning of the 1st stage it is necessary to change the *q*-value by 4÷5 when the beam crosses two adjacent sector boundaries. But at the end of the stage the *q*-value should vary only by 1 after passing 10 sectors. In the latter case the asynchronous condition during the beam transfer from sector to sector is provided only by the change of the parameters of the magnetic field (intensity, length and dipole position in a sector).

The tables also show that the magnetic field in each sector has individual parameters, which are in general too far from optimal. Here, for simplicity of the consideration, it was assumed that each sector contains only one bending magnetic block. Therefore, the length of the magnets is going to be in some cases unrealistically large (30÷40 m). This means that to specify the real layout for the calculations it is necessary to define the optimal sector structure along with its parameter optimization. As a result of this procedure, the different number of the magnetic blocks in the sectors will appear in some cases. Sometimes, it will probably be favorable to use a magnetic structure of a "wiggler" type for the trajectory elongation. This will certainly affect the focusing properties of the sectors.

The large length of the free intervals L_a and L_b (35÷60 m) will allow a sufficient number of magnetic lenses to be installed there.

According to the theory of longitudinal movement [7], one will not envisage any problem with longitudinal focusing of the beam, because of a small number of turns (27 in each stage [8]).

The strength of the magnetic field in the sectors is so small (0.03 ÷ 0.35 T) that the manufacturing of small-sized magnetic elements will not be a problem even in the case of a large-aperture vacuum chamber (8÷10 cm) and a constant value of orbit separation (δR = 15 ±0.1 cm).

Besides, the above tables show that the radial coordinate of the beam jumps only in the last sector. Though this results in increasing "individuality" of the magnetic parameters of the sectors, this has also some technical advantages in comparison with the uniform change of the coordinate from sector to sector when accelerating cavities with gap increasing with radius are used. A "transit - factor" value T_{trans} = 0.95 is used in simulation. It was proposed to consider a modern design of accelerating cavities [8,9], ensuring electrical fields in the range 5.0÷10.0 MV/m with a frequency of 50 MHz.

It is necessary to note that during the adjustment of the magnetic system parameters a number of bunches could be lost in the process of hopping from one harmonic to another. Therefore, the magnetic system parameter optimization should be performed at the reduced intensity of the beam.

The average radii of both ACRC stages have close values (102 and 109 m) to ensure their installation in a single radiation shielded tunnel of width 14÷15 m with a possibility of installing 10-MeV injectors in the same tunnel.

The conditions for acceleration of a high-intensity beam at ACRC are much better (small number of turns, wide aperture, etc.) than at HERA. This is why the minimal current 140÷200 mA can be estimated with some degree of optimism for this facility. A further increase in intensity is possible by installing identical cyclotrons one on top of the other with the use of common accelerating cavities [10].

The rough cost estimation for one level ACRC gives $300÷500, based on the construction cost of traditional three-stage cyclotrons for energy of 1 GeV and current of 10 mA, see Ref.[8].

Detailed numerical calculations of specific variants, the choice of the type of injectors, modeling of systems, optimization of parameters, etc. are not considered yet in the paper.

Conclusions

It has been shown that there are no principal limitations for designing and constructing an ACRC-type facility.

The above-mentioned problems, accompanying the designing and construction of the ACRC, are of temporary nature and their solution would be paid back due to complete matching to all of the above requirements to the facility with the ADTT application.

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