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HIGH-CURRENT CYCLOTRON INJECTOR

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INTRODUCTION

When designing the meson and neutron generator in JINR (project MINGEN), one is to develop and model a deuteron accelerating complex of energy 800-900 MeV/nucl. and intensity 1-100 mA /1/. To accelerate a deuteron beam, two cyclotron facilities are supposed to be used, including DC-1 with the injection energy 7.5 MeV/nucl. and final energy 45 MeV/nucl.

However, the mode of acceleration with the separated orbits, which ensures a 100% extraction of the beam from the accelerator chamber with the same number of revolutions for all particles, is impossible in DC-1 at the beam intensity over 10 mA /2/. Bearing this in mind, one can provide the injection of a 1-10 mA beam in DC-1 by means of a high-current cyclotron injector (HCI), which could also be used for research purposes. The problem of obtaining currents over 10 mA in cyclotrons is not now solved both theoretically (highly efficient beam extraction) and experimentally. One can also discuss the idea of developing a cyclotron facility of the order of 4.5 m in diameter for a beam with the intensity 1-10 mA. In this case the HCI can also be considered as a prototype central region of a 45 MeV/nucl. cyclotron.

PROBLEMS OF HIGH CURRENT

The accelerator CYCLONE-30 can be regarded as the closest analogue of the HCI. Its high current and high efficiency are combined with the advantages of a compact and sector cyclotron [3]. However, the dominating feature of the HCI is a higher beam intensity, which causes some difficulties to be taken into account when choosing the parameters of the HCI systems:

- space charge effects at the axial injection of the beam lead to a considerable decrease in the injection efficiency [4];
- axial stability of a high-current beam can be ensured from the first revolution only at large values of the azimuthal variation of the magnetic field (flutter);
- calculated high efficiency of the beam extraction can be achieved in the acceleration mode close to the mode with the separated orbits (radius modulation of the particle density); it is very difficult to obtain a mode like this;
- special measures should be taken when transporting a high-current beam and matching it with the acceptance of DC-1.

SELECTION OF PARAMETERS

One of the main problems determining the HCI idea is to obtain a sufficiently large flutter on the first orbit of the cyclotron in order to keep the axial envelope of the beam with the intensity up to 10 mA and the minimum injection energy within the magnet aperture.

To solve this problem, the distribution of the cyclotron magnet field of the given spatial structure was calculated with a system of programmes described in Ref. [5]. The beam dynamics

in the central zone of the accelerator was analysed using the set of programmes BEAM [6] and the programme NAJO [7]. Then the dimensions, the field level, the Ampere-turns of the new configuration of the system were determined, and the process was repeated until the acceptable result was obtained.

When calculating the betatron oscillation frequencies in the closed equilibrium orbits, it was found that the axial frequency Qz = 0.8, which is necessary for beam retention, can be obtained from the first revolution (the injection energy is 0.15 MeV/nucl.) at the magnet gap of 2 cm for the 3 sector spiral structure (N = 3). However, the dynamic calculations of the beam transport showed that it is enough to use the radial-sector structure for N = 4, which is practically more convenient. In this case Qz = 0.55 at the 1st revolution, but starting from the second revolution Qz > 0.7 at the chosen energy gain per revolution, owing to the radial motion of the beam.

The table lists the main HCI parameters obtained in the investigations. Below the numerical data of the table are discussed.

Table

Items		Values
BEAM		
type of ions		$2\ D\ 1^+$
energy (MeV/A)		7.5
maximum intensity	(mA)	1-10
	(pps) * E16	0.6-6.3
rotation frequency (MHz)		9.281
betatron frequencies:	Q-R	1.06-1.11
	Q-Z	0.63-0.78
number of turns		31
power in the beam (kW)		15-150

Cont.

MAGNET STRUCTURE	
number of sectors	4
sector angle (degrees)	40-50
sector shim height (cm)	24
air gap (cm)	2-3
magnet height (cm)	80
magnet diameter (cm)	200
amper-turns per pole (MA)	0.15-0.24
Field	
aver.field in the center (Tesla)	1.2187
cyclotron radius (cm)	514.08
aver.field (Tesla)	1.18-1.19
flutter	0.29-0.51
main harm. amp. (Tesla)	0.9 -1.2
hill field (Tesla)	1.9 -2.0
valley field (Tesla)	0.4 - 0.5
field shaping by:	side shim
R.F. SYSTEM	
nber of dees	2
dee angle (effective) (degrees)	15
energy gain per turn (MeV/A)	0.26
harmonic mode	8
frequency (fixed (MHz)	74.25
dee voltage (nominal) (kV)	150
INJECTION	
type of injection	axial
injector potential (kV)	300
injection current (mA)	13-130
type of source (external)	duaplasmotron
type of inflector	hyperboloid
Furst turns in cyclotron	
method of injection	accel.
emittance	
- horizontally (pi*mm*mrad)	5*8 = 40
- vertically (pi*mm*mrad)	5*4.8 = 24
- longitudinally (pi*deg*permille)	9*4 = 36
injection radius (cm)	8.7
turn separation (cm)	5.5
EXTRACTION	
extraction radius (cm)	63
turn separation (cm)	0.8-1.4
type of deflector	electrostat.
extraction efficiency (%)	90-95

MAGNET SYSTEM

After choosing the necessary number of the sector shims and the range of the operation radii the magnetic system elements were investigated for being optimal within the constructed calculation model. The following parameters were considered:

- the angular dimension of the sector shims at which the value of the flutter is not reduced;
- the yoke thickness;
- level of the winding excitation at the given value of the magnetic field;
- initial and final radii of the sector shims for the required field distribution in the beam injection and extraction zone.

The calculated parameters of the magnetic system are listed in the table, and the general view of the magnet (a computer model) is shown in Fig. 1. The obtained values of the ampere-turns of the magnet allow a "warm" version of the system, and yet, the research purpose taken into account, the use of the superconducting winding is considered.

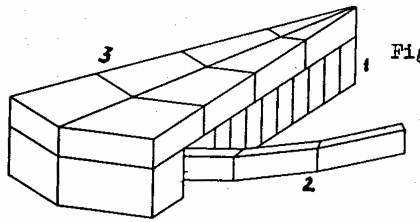

Fig.1. General view of the magnet. 1 - sector shim, 2 - winding, 3 - yoke.

The required azimuth mean magnetic field is supposed to be formed by changing the angular dimension of the shims. Since the energy gain per turn is sufficiently large (the number of turns is small), there are no strict requirements to the accuracy of the field formation. Besides, the energy and type of the accelerated particle are fixed, which allows the field to be formed by means of the ferromagnetic elements alone.

The theoretical dependence of the isochronous mean field on the radius at the given flutter was determined on the basis of Ref. /8/; further, in the analysis of the beam dynamics it was refined in order to minimize the particle phase deviation with regard to the RF field.

RADIO-FREQUENCY ACCELERATING SYSTEM

It consists of two 15-degree dees operating at the 8th harmonic with regard to the particle rotation frequency. The dees are placed in two vallies between the sector shims. Thus, two other vallies can be used to place the devices for beam injection, extraction and diagnostics. The vallies are quite high (see the table), it allows a large value of the RF amplitude of the voltage 150 kV and thus a large energy gain per turn. The design of the RF system can largely involve the solution obtained for CYCLONE-30.

AXIAL INJECTION

The axial injection system is supposed to consist of the following basic elements:

- a duaplasmotron-like source of particles. If the beam current is 10 mA and the expected injection channel efficiency is about 8%, the current to be taken from the source must be of the order of 130 mA;

- a buncher for the best matching the beam to the longitudinal acceptance of the first turns in the cyclotron. The space charge effects, however, largely reduce the efficiency of the buncher;
- longitudinal beam focussing elements (a solenoid, lenses) whose parameters are tuned according to the given beam intensity;
- a hyperbolic inflector /9/ that allows a smaller electrode potential than inflectors of other types. It is important at a large injector potential (300 kV);
- beam diagnostic blocks.

One of the main problems is transporting a high-current beam from the injector to the first cyclotron turns. The transverse motion estimations can be performed on the basis of the Kapchinsky-Vladimirsky equations /10/. The parameter Q, characterizing the beam self-field, is defined by the following expression:

$$Q = b \frac{I}{V_{inj}^{3/2}} ,$$

where I is the beam current, V_{inj} is the injector potential, b is the proportionality coefficient.

When comparing the HCI axial injection and the injection in the U-200 cyclotron by the parameter Q /11/, one finds that the transverse focussing efficiency is the same.

BEAM DYNAMICS

The analysis of the beam dynamics after passing the injection channel highlighted the problem of creating conditions for the non-growing of the effective emittance of particles during their acceleration to the final radius in order to obtain the magnetic field map and the RF system parameters.

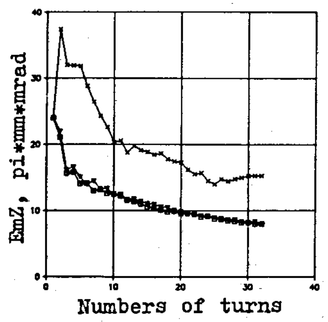

Fig.2. Effective emittance of the axial motion as a function of the turn number. 1 - 0.3 mA, 2 - 8 mA, Er = 20π mm mrad; 3 - 8 mA, Er = 40$\pi \cdot$mm mrad.
0.3 mA
8 mA, EmR=20
8 mA, EmR=40.

It is seen from Fig. 2 that if the charge density in the bunch corresponds to the current of 8 mA and the initial radial emittance of 20 π mm mrad, there is a considerable increase in the effective axial emittance due to the beam space charge. The effect is best noticeable in the zone of the first turns, where the flutter has the smallest value and the relative velocity of the particles v/c is small. Yet, the axial envelope of the beam remains within the magnet aperture. If the initial radial emittance grows to 40 π mm mrad, the space charge effects are reduced to a minimum (Fig. 2, curve 3).

As far as the radial emittance is concerned (Er), one observes its considerable increase in the first several turns in the central zone of the accelerator (Fig. 3, curve 1); the increase is determined by the RF field resonance effect on the beam /12/. The optimal correction of the effect was introduction of the 1st harmonic of the magnetic field with the maximum am-

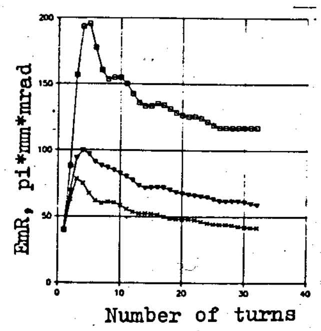

Fig.3. Effective emittance of the radial motion as a function of the turn number. 1 - 0.3 mA; 2 - 0.3 mA, Bm1-correction, 3 - 8 mA, Bm1-correction.
0.3 mA
0.3 mA, correction
8.0 mA, correction.

plitude of the order of 15 mT at the corresponding dependence of the amplitude and the phase on the radius. The correction exemplified in Fig. 3, curve 2, for I = 0.3 mA. If the beam intensity is changed, the obtained relations of the amplitude and phase of the 1st harmonic are not optimal any more (Fig. 3, curve 3) and should be tuned according to the chosen beam intensity.

BEAM EXTRACTION

The particle current in the zone of final radii being small, quite a distinct radius modulation of the beam density (Fig. 4) is observed for the single-turn separation of the extracted particles by means of the electrostatic deflector with the 90-95% efficiency. However, when the intensity grows to 10 mA, the longitudinal space charge effects lead to the partial overlapping of the orbits. In this case the particle injection with the above efficiency can be performed by one of the earlier investigated methods /2/.

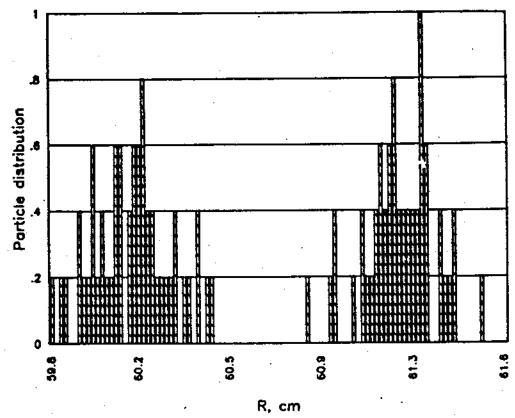

Fig. 4. Radius distribution of the particle density in the extraction zone at I = 0.3 mA.

BEAM TRANSPORT IN DC-1

The main problems of the high-current beam transport from one accelerator to another are described in Ref. /13/. Among them the problem of matching the emittance at the HCI exit to the acceptance of DC-1 is of special interest. The parameters of the RF system are chosen such that the time structures of the beams in the HCI and DC-1 are matched:

$$h_1 f_1 = h_2 f_2 ,$$

where h is the harmonic number, f is the frequency for the HCI (index 1) and DC-1 (index 2). As far as the emittance at the input of the deflector of the device for the beam extraction from the HCI is concerned, its value does not exceed the one established for injection in DC-1.

CONCLUSION

1. The proposed version of the high-current injector for DC-1 ensures the acceleration of the deuteron beam with the intensity 1-10 mA in a cyclotron facility 2 m in diameter.

2. A specific feature of the high-current facilities in the intensity range mentioned is the necessary tuning of the cyclotron parameters to the given value of the particle current. It involves high-level automation of the accelerator control.

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