103 AND 60 CM COMPACT CYCLOTRON ENGINEERING

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Abstract

On the basis of general design principles two compact cyclotron models with pole diameters of 103 and 60 cm have been worked out at the D.V. Efremov Institute for scientific research as well as for various applications. Operating data for the larger cyclotron is presented; the 60 cm cyclotron is now under construction.

1. Introduction

The 103 cm cyclotron is designed to accelerate hydrogen and helium ions in the energy range from 5 to 20 Z^2/A MeV. The beam intensity at maximum energy amounts to 200 μA on an internal target and to 70-100 μA on an external one. Design parameters of the above accelerator were reported earlier [1,2]. Since 1973-4 two machines have been used in the cities of Leningrad and Turku, Finland, for applications as well as for such physics studies as short-lifetime-radionuclide production for medical diagnostics, activation analysis, nuclear structure and nuclear spectroscopy studies, and also for improvements of the machine. The 60 cm compact cyclotron is designed for deuteron acceleration up to an energy of 3 MeV at the external beam intensity of 100 μA. An activation analysis of light elements in the matrices of heavy materials appears to be its special application.

2. Basic Parameters of the Current Cyclotrons

The current compact cyclotrons could be characterized by a number of advantages natural to them, such as small magnet gaps, moderate sizes, relatively low energy consumption and easy operation and handling.

The basic specifications of the main 103 and 60 cm isochronous sector focusing cyclotron units are listed below in Tables 1 and 2.

Table I. Basic specifications of the 103 cm cyclotron units

Magnet	
Type	H-shaped
Pole diameter, cm	103
Air gaps "hill"/"valley", cm	7,2/12
Number of sectors, pairs	3
Field spiral angle at final radius, deg	35
Average field, T	1,45
Number of trim coils, pairs	4
Number of harmonic coils, sets	2
Weight, tons	24
Maximum power consumption, kW	40
RF System	
Number of dees	2
Dee angle, deg	
at final radius	140
at half of that	180
Dee aperture, mm	19
Dee/liner gap, mm	15
Dee voltage, kV	30
RF frequency range, MHz	8,5-26,0
RF power, kW	50
Ion Source	
Type	hot cathode
Chamber injection	axial
Arc power	up to 1 kW
Extraction system	
Electrostatic deflector	
angular span, deg	37
maximum voltage, kV	45
Radial focusing magnetic channel	
length, cm	30
maximum gradient, T/cm	0,1

Table 2. Basic specifications of the 60 cm cyclotron units

Magnet	
Type	cylindrical
Pole diameter, cm	60
Air gaps "hill"/"valley", cm	5,5/10,3
Number of sectors, pairs	3
Field spiral angle at final radius, deg	25
Average field, T	1,4
Number of harmonic coils, sets	2
Weight, tons	7
Power consumption, kW	25
RF system	
Number of dees	1
Dee angle, deg	180
Dee aperture, mm	19
Dee/liner gap, mm	10
Operating RF frequency, MHz	10,7
RF power, kW	6

Ion source and extraction system are similar to those used in the 103 cm cyclotron.

3. Design features and parameters of the 103 cm cyclotron

The construction improvements of the 103 cm machine main units aimed at increasing reliability have been brought about by intensive computations and experimental studies.

The magnetic field in the 103 cm cyclotron is of an n = 3 sector focusing type with a small spiral angle. The magnetic field is pictured in Fig. 1 versus radius for one of the accelerating regimes. When optimizing the sector shape much attention has been paid to the acceleration isochronism as well as to reducing the number of trim coils and their power consumption. In the final state the sectors had a constant width with the boundaries formed by arcs. Isochronous ion acceleration calculations in the desired energy range made it clear that resultant fields provided a phase shift of less than 5-8 degrees. This is within the range of uncontrollable departures produced by field instabilities. The power consumption of the trim coils does not exceed 0.5% of that of the main one.

In the central region of the magnetic field, owing to axial ion source position, the isochronous and stable acceleration requirements were met by setting the first

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harmonic of the azimuthally varying magnetic field to 18 mT with the maximum at a radius of approximately 3 cm.

The RF system consists of a two-dee panel resonator, an oscillator, and an automatic control system which ensures an acceleration voltage of stable amplitude and phase. In the range from 8.5 to 26 MHz the operating frequency variation is remotely controlled by means of resonator panels and trim capacitors. The RF oscillator circuit for independent excitation is constructed with a broadband amplifier. The final amplifier stages are mounted on the resonators which are actually their loops. Such RF system construction makes the system retuning much easier and provides a long-term frequency stability of 10^{-7}. The external resonator natural frequency instabilities are handled with an automatic regulation system. Another system provides an accelerating voltage stability of 10^{-3}.

Beam dynamics could be briefly described as follows. It should be noted that an ion source of a fixed location as well as a voltage of a fixed magnitude are used for all the acceleration regimes. Orbit centering, when it is required by changing an ion type or by ion energy variation, is simply provided by the central harmonic coil, which is quite able to displace ion orbits up to 12-15 mm. Fig. 2 shows the orbit center displacement corresponding to an initial beam emittance of 200 mm·mrad at an energy of 30 KeV when entering a source-puller. An initial phase ranges from -30 to +10 degrees. The equilibrium orbit is also shown there. The vector representing the effect of the central harmonic coil is chosen in such a way as to compensate the coherent radial amplitude. Practically, the coherent amplitude was always less than the incoherent one, which did not exceed 2-2.5 mm.

In the main zone the equilibrium orbit beam turns out to be driven off the magnet center. There are a number of factors which make the orbit center displacement real, such as the so-called gap crossing resonance, the lower harmonics of the azimuthal magnetic field inhomogeneity, and the radially extended external harmonic coil used for extraction optimization. The magnitude of the total displacement depends on the sum of the above contributions and amounts to 3-4 mm.

The orbit center displacement does not deteriorate the quality of a beam because orbit center precession does not occur. During acceleration the beam remains on the dynamical equilibrium orbit with a center displacement which can readily be found by calculation.

When extracting a beam an additional magnetic field is generated by the external harmonic coil. The phase and the amplitude of an additional field is so chosen that the beam could be displaced by means of the first main field harmonic and the gap crossing resonance to get a maximum turn separation at the septum due to precession in the decreasing magnetic field just after passing the $\nu_r = 1$ resonance. The calculated turn separation appears to be more than 5 mm after passing through the resonance zone, which makes it possible to use a septum thick enough (up to 1-1.5 mm) and to get a highly effective extraction (up to 70-80%).

The beam parameters presented below were obtained on two machines [3]. The internal beam intensity amounts to 200 μA and the external one to 70-100 μA. The beam intensity limitations for hydrogen ions are different in principle from those for helium. When accelerating protons and deuterons, the internal beam intensity is limited by a target (4 kW), whereas the external one is limited by the tolerable losses in a deflector septum (1 kW). The intensity of $^3He^{+2}$ and $^4He^{+2}$ is limited by the arc power in the ion source channel (0.7-0.8 kW).

One can clearly see the high quality of the 103 cm cyclotron beam in Figures 3 and 4. The radial beam intensity separation obtained by means of a ΔR-probe as well as the 19 MeV proton energy spectrum taken by the 115 degree analyzing magnet are shown there.

It should be emphasized that the 10 μA intensity was obtained after the proton beam passed through the two 1 mm slits of the analyzing magnet with an energy dispersion less than 0.1%. The internal beam current was 70 μA was focused on the first slit of the analyzing magnet.

4. Design features of the 60 cm cyclotron

The 60 cm cyclotron is designed to accelerate deuterons to a fixed energy of 3 MeV. So the construction of its magnetic and RF systems turns out to be much simpler. The cylindrical magnet has 16 mm thick sectors which produce an isochronous radial profile of the average magnetic field. The RF system with a 180 degree dee operates on a fixed frequency of approximately 11 MHz. Many features of the previous 103 cm machine have been realized in the 60 cm model; these include the power supply system, the ion source, the initial motion, the beam extraction and the construction of a number of units. Fig. 5 presents the general layout of the machine which is now being built.

References

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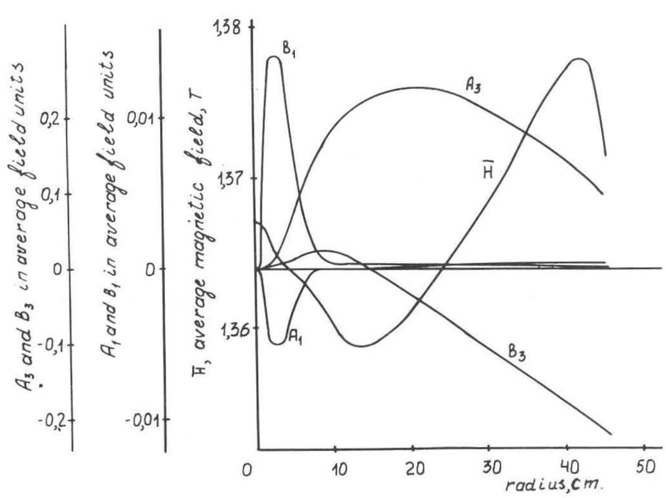

Fig. 1. Cyclotron magnetic field versus radius.

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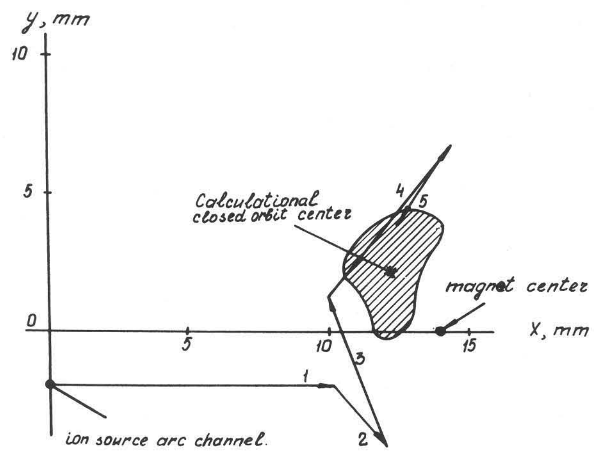

Fig. 2. Vector orbit center motion when accelerating to a half of the final radius. Central magnetic field is 1.36 T. Protons are accelerated at a dee voltage 30 kV. 1 - analytical approximation; 2 - electrical field real distribution; 3 - A_1 influence in the center; 4 - gap crossing resonance effect; 5 - central harmonic coil effect. The orbit center area is dashed in the figure.

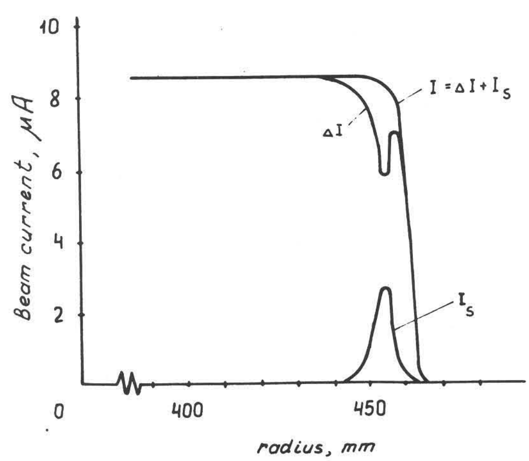

Fig. 3. Radial beam intensity distribution measured by ΔR - probe. I - total current, ΔI - differential probe current (at a probe width of 2 mm), I_S - differential probe screen current.

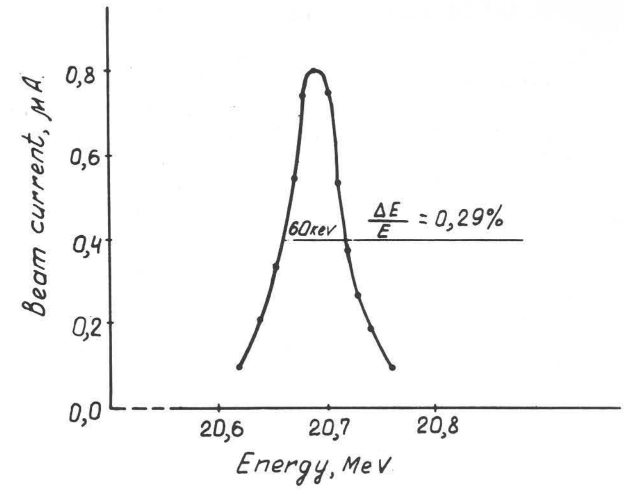

Fig. 4. External beam energy spectrum. Protons are accelerated up to 18 MeV.

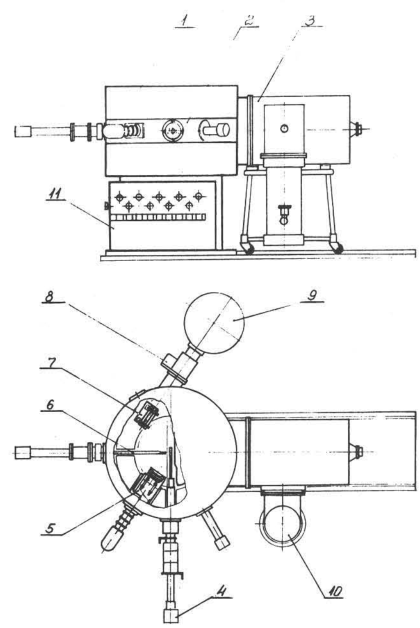

Fig. 5. General layout of the cyclotron; 1 - magnet; 2 - vacuum chamber; 3 - RF-system; 4 - ion source; 5 - deflector; 6 - ΔR - probe; 7 - magnetic channel; 8 - valve; 9 - target chamber; 10 - vacuum unit; 11 - water-distribution panel.

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