APPLIED LOW-ENERGY CYCLOTRON

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Abstract

Design parameters of the cyclotron intended for the acceleration of protons at an energy ranging from 0.2 to 2.5 MeV at an extracted beam current of 200 μA are presented in the paper. The features of the cyclotron are its small overall sizes and low energy consumption. The cyclotron is equipped with a computer control system. The machine can be applied for studies of the radiation resistance of radio-electronic components and structural materials as well as for the element express analysis using such methods of nuclear physics as PIXE, RBS and resonance nuclear reactions.

In addition, energy variable over a wide range allows profile distribution studies of implanted materials. With this aim in view, the cyclotron can be equipped with a beam transport line with a scanning system and a chamber for material irradiation.

INTRODUCTION

A source of accelerated protons with energies ranging from 200 keV up to 2.5 MeV with a beam current of 120-150 μA and energy spread of no more than 0,5 % (FWHM) is of obvious interest for the research into the radiation resistance of structural materials and radio-electronic components. Irradiated objects are up to 30×30 cm in sizes, and in this view the accelerator should be equipped with a beam transport line and a system for beam scanning along the surface of an inspected object.

Important requirements are: simple and reliable operation, low energy consumption and computer control of the machine. Nowadays, high- voltage accelerators are used to produce beams with the characteristics mentioned above. The machines offering such advantages as high energy stability, low emittance of the beam extracted from the ion source and continuous mode of operation, however, suffer from such serious drawbacks as large dimensions and high cost.

Cyclotrons are known to be widely applied in the research into the radiation resistance of the structural materials of nuclear reactors as well as for studying the wear of units under stress. For these purposes beams of protons, deuterium ions and multi-charged high energy ions (10-30 MeV/nucleon) are used. In the Karlsruhe Laboratory, 26 MeV proton beams are extracted through a thin foil into the atmosphere and transported into a special chamber with samples under study. Similar works were done on the U-150 cyclotron in Obninsk.

In modern isochronous cyclotrons allowable significant reduction of the accelerating voltage amplitude and, correspondingly, air gaps of the electromagnet makes possible reduction of the weight, sizes and energy consumption of the whole facility. The RF system operates in the continuous mode, and there are no problems in the production of a 100-200 μA (and higher) beam of protons. Thus, cyclotrons can be considered as a potential source of accelerated protons with energy of several MeV.

CHOICE OF CYCLOTRON PARAMETERS

In late eighties a DC-3 cyclotron was designed and manufactured in NIIEFA for the acceleration of deuterium ions up to a fixed energy of 3 MeV. When the amplitude of the voltage across the 180° dee was 14 kV, the beam current at the final radius was 500 μA, and that at the external target amounted to 150 μA. The machine weight was 5 tons, energy consumption – 35 kW [1]. The cyclotron was used for activation analysis – to determine the content of light elements in the matrices of heavy metals.

The new cyclotron project is distinguished with a comparatively low energy of accelerated protons and energy variation over a range of 0.2-2.5 MeV.

The acceleration process on this cyclotron can be schematically divided into three stages. The first is the motion of ions in the center, which is characterized with changes in the position of orbit centers and grouping of the phases captured in the process of acceleration. Usually up to the 6-10th turns, the position of orbit centers is stabilized, which points to the beginning of the 2nd stage – the acceleration of ions in the isochronous mode. The duration of this stage depends on the cyclotron energy and amounts to from several tens up to several hundreds of turns. At the 3rd stage the beam is deflected from the final radius and extracted to external target (1-2 turns); thus the acceleration process is finished.

In the considered case at a minimum energy of the cyclotron of 0.2 MeV, the energy gain is reduced, as the number of turns in the process of acceleration should be not less than 20-25. Consequently, the energy gain per turn should not exceed 8-10 keV. At a maximum energy of 2.5 MeV, the energy gain can be increased up to 25-30 keV, and the number of turns in the process of acceleration can be respectively increased up to 80-100.

In connection with the above-said, the choice of the accelerating structure parameters should be grounded on the practical feasibility of minimum energy gain per turn, ΔW. As is well known, $\Delta W = 2nU_d \mathrm{Sin}(q\vartheta/2)$, where n is the dee number, U_d is the amplitude of the accelerating voltage across the dee, q is the harmonic mode of the accelerating voltage frequency, ϑ is the dee azimuthal length. Thus, the minimum energy gain occurs in an accelerating structure with a single 180° dee. Unfortunately a single dee with the angular length different from 180° cannot be used because of the microtron effect resulting in the drift of orbits and loss of radial stability. The values of energy gain given above take place when the amplitude of voltage across the dee is chosen from 4 up to 15 kV and the minimum amplitude value corresponds to low magnetic field induction, that is important when centering orbits and for detouring the ion source head.

In the energy range between 0.2 and 2.5 MeV the magnetic rigidity of protons is varied from 0.0646 up to 0.2284 Tm. If the magnet pole diameter is taken to be 600 mm, the final acceleration radius is ~260 mm. The magnetic field strength should vary from 0.248 up to 0.879 T, and the proton rotation frequency- from 3.79 up to 13.42 MHz. The machine can operate at q = 3, and taking this fact into account, the frequency range must be 3. The smaller possible value of the frequency band lower boundary is preferable, however, this results in larger sizes of the resonance system. The frequency band of 8-24 MHz is a reasonable compromise.

Low magnetic induction and weak relativistic effect of accelerated protons (β_{min} = 0.0206 at W = 0.2 MeV, β_{max} = 0.073 at W = 2.5 MeV) make much easy the formation of required magnetic field. In the design range of energy variation the radial increase of the average magnetic field is from 0.05 up to 2.3 mT (0.5-23 G). The azimuthal variation applied in the magnetic field at a level of 10-15% from the average value is sufficient for effective beam focusing in vertical direction.

An electrostatic deflector and radically-focusing magnetic channel will be used for beam extraction. In the beam extraction area turns are separated due to precession of orbit centers by introducing the controlled first harmonic of the magnetic field. Comparatively low strengths of the deflector electric field (50-80 kV/cm) are sufficient for effective beam extraction. No difficulties are expected to emerge with the septum cooling, as its heat losses will amount to no more than 200-300 W. The septum activation will be also low, and therefore no problems with repair/maintenance works in the vacuum chamber of the cyclotron are anticipated.

From the known voltage across the dee, the air gap of the electromagnet can be found. It is formed by: the dee aperture – 10 mm, thickness of the dee covers – 6×2 = 12 mm, high-frequency gap – 12.5×2 =25 mm, sectors with liners – 10×2 = 20 mm; totally – 67 mm in the "hill" and 87 mm in the "valley". The "valleys" house low–power gradient coils, which can be also used for the correction of the first harmonic of the magnetic field azimuthal instability.

Main Parameters of the Cyclotron:

- Accelerated ions…………………………….. H^+
- Energy (variable), MeV…………………0.2-2.5
- Energy spread (FWHM), %..........................0.5
- Current, μA…………………………………200
- Irradiation field sizes, mm2……………300×300
- Proton flux density on target, nA/cm^2…..0.1-100
- Beam current
  instability for 1 h, %.................not worse than 5
- Flux density inhomogeneity on
  irradiated surface, %..................no more than 20
- service life of the ion source cathode, h…….200
  (can be replaced within 20 minutes)

Power Consumption

- Stand-by condition, kW……………………<15
- Beam on target, kW…………………………35

Magnetic Structure

- Shielding type magnet
- Pole diameter, cm……………………………60
- Number of sectors (per pole)…………………4
- Average induction, T…………………...0.3-0.9
- Gap (hill/valley), mm……………………70/90
- Overall dimensions, mm:
  - outer diameter…………………………1300
  - height…………………………………1000
- Magnet weight (Fe/Cu), t…………………5/0.6
- DC power in coils, kW………………………..5

Radio-frequency System

- Number of dees……………………………….1
- Dee angle…………………………………1800
- Harmonic mode………………………...1 and 3
- Frequency range, MHz…………………….8-24
- Dee voltage amplitude (max), kV……………15
- Dissipated RF power per dee, kW…………….7
- RF oscillator output power, kW……………..10

Ion Source

- Type of source………………………………PIG
- Location……………………………….....internal
- Arc power, kW………………….……………..1

Beam Extraction and Diagnostics

The beam is extracted with an electrostatic deflector with radially focusing magnetic channel. A water-cooled internal probe with remote control is used for the cyclotron adjustment.

Pumping System

- Number of diffusion pumps…………..……….2
- Pumping speed, l/s…………………………3500
- Mechanical pump with
  pumping speed, l/s……………………………10
- Operating vacuum, torr………………(1-2)·10^{-5}

Beam Transport Line and Scanning System

The beam of accelerated protons via the beamline is transported from the cyclotron to the target chamber where samples up to 300×300 mm are irradiated. The beamline is equipped with an independent pumping system, electromagnetic devices for correction of the beam position, beam focusing, measuring the beam parameters and beam scanning across an irradiated sample.

Control System

The control system of the cyclotron is based on a programmable controller with a computer. The control system includes a control rack, a control console of table-top type with a computer and keyboard.

CYCLOTRON LAYOUT

The cyclotron may have a standard layout (Fig. 1), similar to that of the DC-3 cyclotron, with the only difference-the resonance system with a triple frequency range. The dee in the chamber can be mounted on the insulator, and in this case the device for adjustment of the resonance system frequency can be located at atmospheric pressure.

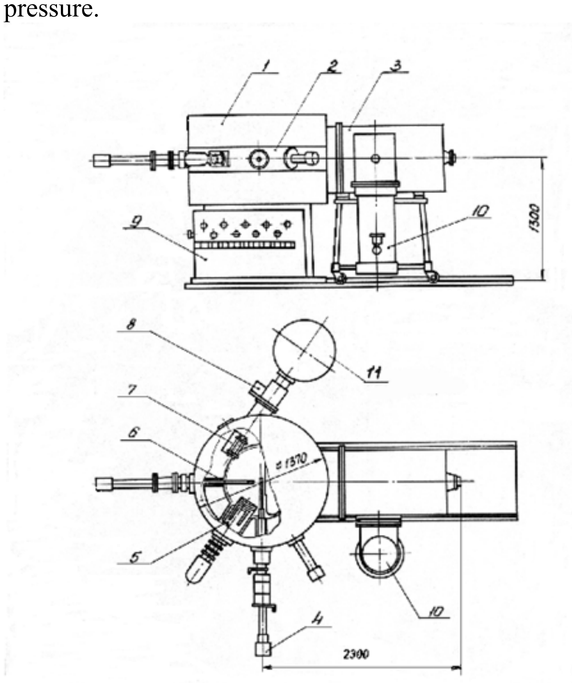

Figure 1: General view of the cyclotron.
1 – magnet, *2* – accelerating chamber,
3 – resonance system, *4* – source, *5* – deflector,
6 – probe, *7* – magnetic channel, *8* – gate valve,
9 – water distributing board, *10* – vacuum pump,
11 – target chamber.

REFERENCES

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