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PROCEEDINGS

AIC-144 cyclotron: present status

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Abstract The presented AIC-144 cyclotron was designed and constructed 20 years ago in the Institute of Nuclear Physics in Kraków (Poland). Later on it was modernized, after the decision of creating the Hadron Radiotherapy Centre in Kraków was taken by the government. At present, the cyclotron is capable to deliver beams of protons (with energy up to 60 MeV), deuterons (with energy up to 30 MeV) and α-particles (with energy up to 60 MeV). The magnetic structure and the RF system were modernized (a new HF generator with output power 120 kW and frequency range 10–27 MHz was installed; an RF cavity resonator was reconstructed to improve the Q-factor at the highest frequencies). The new PIG source and system of central diaphragms was built to improve beams quality on the first turns. The single lamella and multilamella probes were fully reconstructed. Special effort was put on a highly efficient extraction system. The precession method for particles extraction was chosen as the best one. All computer simulations and experimental runs were done in close cooperation with specialists from the Laboratory of Nuclear Problems JINR, Dubna. The extraction system consists of 2 electrostatic deflectors, 3 magnetic channels (passive) and 4 coils for shaping of the 1st harmonic. So far, the beam extraction experiments were carried out for the proton beams with the final energy of 35 MeV, 48 MeV and 60 MeV. For all these energies the efficiency of extraction was above 50%. A computer remote control of the main magnet power supply and of the 24 correction coils was installed and put into operation. In the last 3 years, the internal beams of protons and α-particles were used to produce radioisotopes like ^{11}C, ^{57}Co, $^{83-85}$Sr, ^{102}Rh, ^{111}In, $^{173-175}$Hf, $^{178-181}$W.

Key words cyclotron • extraction system • HF generator • proton beam • deuteron beam

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Introduction

The first step in the development of the cyclotron technique in Kraków was made 50 years ago, when in 1952, Professor Henryk Niewodniczański proposed to build a cyclotron at the Institute of Physics of the Jagiellonian University. The team of physicists and engineers designed and constructed, in cooperation with the Polish industry, the first cyclotron in Poland. The first protons were accelerated to the energy of 3 MeV in December 1956. Two years later the so-called "small cyclotron C-48" was transferred to the new building of the Institute of Nuclear Physics at Bronowice, a suburb of Kraków. After it was assembled, put into operation and upgraded, it was commissioned in 1958. The C-48 cyclotron was applied to research in physics and nuclear techniques (RBS, channeling, Pixe, Pige and so on). In 1992, the C-48 cyclotron was delivered to the Maria Curie-Skłodowska University in Lublin, where it is used for the solid state physics research and in medicine.

The next cyclotron: U-120 was made in the Soviet Union and commissioned in Kraków in 1958. Over the next few years, five ion tracks and experimental stands were constructed and put into operation. The U-120 cyclotron was used generally for:

a) physical experiments,

b) radiotherapy – in 1976 the first (and only one of its kind in Poland) neutron therapy stand was commissioned. Therapy was offered to patients of the Maria Curie-Skłodowska Oncology Center in Kraków. One-week cycle of radiotherapy was carried out every month. The treatment results were positive, with up to 34% success rate,
c) radiobiological research,
d) radioisotope production.

The U-120 cyclotron worked until 1995.

At the end of the 1970's, theoretical studies and design of a new isochronous cyclotron started. This work was carried out by the staff of the newly organized Department of Acceleration Technique under the leadership of Dr J. Schwabe. Over the later years, other Polish construction companies also took part in the design and manufacturing the AIC-144 cyclotron. Large components of the cyclotron such as the electromagnet, chamber, cavity etc. were manufactured by Polish industrial plants. Many cyclotron components were made in the workshop of the H. Niewodniczański Institute of Nuclear Physics in Kraków. Putting into operation of the cyclotron started in 1986. Simultaneously, efforts were made to obtain funds for the transfer of the AIC-144 cyclotron to the vault of the U-120.

In 1994, a task group for launching the Hadron Radiotherapy Center at the Institute of Nuclear Physics was appointed, and at the same time, work connected with the adaptation of the AIC-144 for medical purposes started.

In 1995, the Institute of Nuclear Physics received funds for the transfer of the cyclotrons and as mentioned above the U-120 cyclotron was taken out from the service and the reconstruction of the cyclotron vault for the needs of the isochronous cyclotron as well as its assembly started. This work has been carried out since 1993 under the leadership of E. Bakewicz, M. Eng.

Present status of the AIC-144 cyclotron

General technical description of the AIC-144 cyclotron (before modernization – status in 1994) is given in a paper by J. Schwabe [7]. During the last 8 years all main systems of the cyclotron were deeply modernized or changed.

First of all, the cyclotron U-120 was demounted and on its place (in the vault with appropriate radiation shielding) the AIC-144 cyclotron was transferred (see Fig. 1). A new ground plate was built; the cooling and vacuum systems were reconstructed. The old net of cables and wirings was replaced by a new one (near 10 km overall length!).

Magnetic fields system

The AIC-144 cyclotron has an axial – symetrical magnetic structure. The space, sine – shape structure of the field is formed by four magnetic spirals, two sector rings and a set of magnetic discs (in the central part of the device). The necessary isochronous fields may be obtained and corrected by means of a set of 20 pairs of concentric coils. Each of them is supplied from a power supply with a current stability factor of ca. 10^{-5}. The average magnetic field at the extraction radius $R = 62$ cm (a minimum gap of 10.6 cm) can amount to 1.83 T.

Fig. 1. View from ion source side of AIC-144 cyclotron.

Since for the highest energy of the proton beams (near the extraction radius) a variation of the magnetic fields (flatter) was too deep, we applied a new set of the magnetic shimms. The magnetic system was earlier provided with 2 sets of valley coils for control of the orbits coaxiality. Now, we have only one set of these coils (in the central region). Instead of the second one, we placed a set of four pairs of harmonic coils in order to obtain the necessary value of the first harmonic in the region of the extraction system.

High-frequency system

Many efforts were put into reconstruction of the HF system. Firstly, the existing HF generator was able to generate a radiofrequency only up to 25 MHz, while as for acceleration of protons up to 60 MeV we need 26.15 MHz.

Secondly, the RF cavity resonator had a very low dynamic quality factor (Q) for the highest frequencies. Some difficulties were associated with the system of feeders between the generator and the RF cavity. To solve these problems we decided:

1) To buy a new HF generator, suitable for our needs. The generator was made in St. Petersburg (Russia) by TIRA Corp. It was divided into three parts. The power supply is located in one room. The control panel and the synthesizer are located in the operation room of the cyclotron. The power amplifier is placed close to the cavity resonator. The frequency range of the generator was 10–27 MHz, output power – 120 kW. After modernization of the set of cavity trimmers, we can achive maximum dee voltage in the range of 50÷53 kV. In 2000 a new, high efficiency measuring system of the dee voltage was put into exploitation.
2) During the last years, computer simulation and modeling experiments, in order to improve a dynamic quality factor (Q) of the cavity resonator, were performed. As a result, the cavity was reconstructed. Vertical, moving panels were mounted inside the cavity, in order to reduce the excitation power and to achieve the upper limit of the frequency. The remote control for tuning the resonator was installed. The cavity is excited by means of a new set of inductive loops. At present, the Q-factor exceeds 2000. The cyclotron has only one dee (180°) and its capacity – in relation to the earth – is near to 700 pF.

Power supply system

The power supply system of the cyclotron can be divided into 3 groups. The first consists of the main magnet supply with its remote control system. An old power supply was deeply reconstructed. First of all the current sensor was changed. Now, the supply has a modern, high quality (2 ppm/°C) sensor made by Danfysic (Ultrastab 864 V, 600 A/10 V). The control system was changed. It uses the modules "Advantech, m. 5000" and PC computer for control. Communication between the module "5000" and computer is realized by 485 interface. The code for control and visualization was developed in our Division using a computer program "In Touch, ver. 5.6". A new computer program was worked out (using the Windows 95 operating system) for remote control and monitoring of the group of 20 concentric coils power supplies.

The third group includes a set of modern power supplies for the harmonic coils and for the ion beams transport system. It was made by the Technical University in Wrocław (by Dr J. Duchewicz) and by DORA Power Systems Co. (Wrocław). These are very modern, high efficency, resonant power supplies with remote computer control [3].

Injection system

For the injection of ion beams we use a heated cathode PIG ion source. The position of the ion source in relation to the puller can be changed by means of the remotely controlled servomechanisms. The puller can be moved by a special servo system along the edge of the dee.

In last year, we have elaborated a new construction of the ion source. Now it is manufactured in our Scientific Equipment Division. Firstly, the new ion source will give us a possibility to change the heated cathode without pulling the whole ion source out. Secondly, on this source we shall have remote control of the diaphragms which are responsible for improving a phase shift of the beam on the first orbits. In the future, it will be possible to apply an external ion source with vertical injection, because the yoke and the upper pole are provided with holes of 80 mm diameter.

At present, we have a set of the 6 probes for measurements of the beam currents and symmetry of the orbits. The heads of the probes may be changed from a single one to multilamellas. Three of them are connected with the extraction system.

Transport beam lines and devices for forming of the beams

The transport of the charged particles beam over large distances is inherently connected with the important problem of the reduction of particle losses to minimum. Now, our transport system consists of three bending magnets, three quadrupole doublets and some measuring boxes. In the old system we had five experimental stands. After the reconstruction we have two experimental stands for the physical experiments, three for other applications (radiochemistry, radiobiology, neutron treatments) and a new one for ocular melanoma therapy.

The bending magnets can achieve fields from 0.075 to 0.13 T. The quadrupole doublets have gradients near 8 T/m. The doublets can focus the beams to spots of a 4 mm diameter.

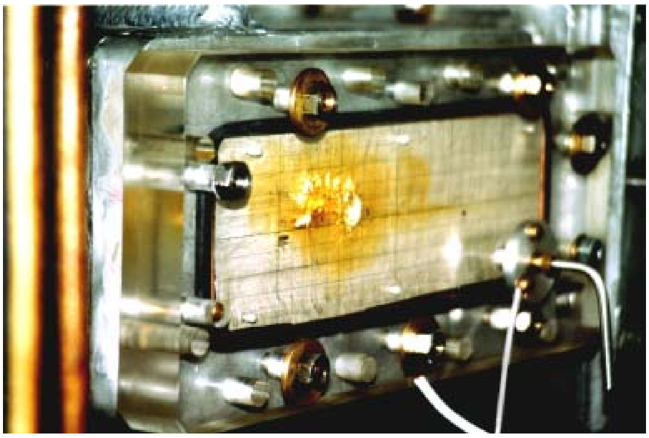

Fig. 2. Image of the beam spot in the window of the vacuum chamber (left upper side) – protons: 45–60 MeV).

Last year achievements

The first proton beam with the energy of 35 MeV and the intensity of 50 nA was extracted from the chamber on 20th June 2000. Next year, a proton beam of 48 MeV (I = 100 mA) was successfully extracted.

In April 2002, protons were accelerated to the energy of 60 MeV (I = 10 μA) and extracted from the cyclotron chamber with the aid of the new extraction system. The proton beam was observed on the cyclotron control panel with the use of a TV monitor (see Fig. 2).

The main AIC-144 parameters are given in Table 1.

Production of several radioisotopes using proton and alpha particles started in 1998. Placing the targets to be irradiated (on the inner beams) in position and taking them out was done manually. In the nearest future these functions will be remotely controlled because the automatic target handling system is almost complete. The radioisotopes given in Table 2 have been produced since 2000.

Table 1. The main parameters of the AIC-144 cyclotron.

Weight of magnet	140 t
Magnet pole diameter	144 cm
Magnetic structure	4 spiral sectors (54°)
Strength of magnetic field	8.5–18 kGs
Electromagnet current	max. 700 A
Number of concentric coils	20
Concentric coils current	max. 400 A
Number of valley coils	4
Valley coils current	max. 250 A
Number of dees	1 (α = 180°)
Dee voltage	50 kV
RF generator	10–27 MHz
Extraction radius	62 cm
Ion source	internal, PIG type
Extraction system	3 electrostatic deflectors and 3 magnetic channels
Acceleration factor	$K = 60$

Table 2. Radioisotopes produced by the AIC-144 cyclotron.

Nuclear reactions	Beams
$^{99-102}Ru(p,n)^{99-102}Rh$	protons: 12 MeV current: 4 μA irradiation time: 20 h
$^{58-64}Ni$ (p,pxn)^{57}Co	protons: 30 MeV current: 2 uA irradiation time: 1 h
$^{11}B(p,n)^{11}C$	protons: 10 MeV current: 23 μA irradiation time: 1 h
$^{168-176}Yb(\alpha,n)^{173-175}Hf$	α-particles: 28 MeV current: 5 μA irradiation time: 24 h
$^{109}Ag(\alpha,2n)^{111}In$	α-particles: 28 MeV current: 1 μA irradiation time: 10 h
$^{11}B(p,n)^{11}C$	protons: 10 MeV current: 3 μA irradiation time: 0.5 h

Computer control system

For the needs of proper control of the cyclotron some computer programs were elaborated:

1. Program for the automatization and calculation of the magnetic fields maps (by K. Daniel).
2. Program for control of the power supplies (K. Daniel, J. Korecki).
3. Program for the calculation of the isochronous fields and proper currents in the main magnet and in the correction coils.

Since 2001, we made efforts to elaborate COHP (Cyclotron Operator Help Program), consisting of some useful modules. The program can help the operator in selecting the isochronous cyclotron operating modes. So far, we have two fully written modules: Cyclotron Analytic Model Program (CAMP) [5] and Betatron Oscillation Frequencies Calculation Program (BORP) [4]. The programs are written with the use of Visual C^{++} v. 6.0. CAMP is used for two aims. The first one (CAMP) is used for mean magnetic field calculation with the allowance for flutter as stand alone program module with the friendly graphical interface for the user. CAMP is used as an intermediate program for debugging and following build – in of the source code of this program into COHP. BORP program is used for the betatron oscillation frequencies calculation. The BORP will be used too as a part of the COHP program. Besides of the CAMP and BORP, the COHP program also covers Structured Query Language (SQL) databases, which are used for storing the measured data and for isochronous cyclotron control.

The modules were checked in Vinča (Jugoslavia) and Ricken Cyclotron Center (Japan) with very good results.

Extraction system

The problem of the effective beam extraction was found to be difficult considering the constraints of the existing cyclotron. The precession method for extraction was accepted by us as the right one [2]. One of the most important issues was the control of the 1st harmonic of the magnetic field distortion due to the deflection system in the area of the internal circulating beam. It was also necessary to modify the field in order to shift the position of the coupling resonance (to limit the axial blow-up of the beam) by applying appropriate valley shims and other available means.

The extraction system of the AIC-144 cyclotron consists of 6 elements located inside the vacuum chamber: 3 electrostatic deflectors and 3 magnetic channels [1]. The 2nd and 3rd electrostatic deflectors (see Fig. 3) are mounted on the same case and are powered by one high-voltage unit. This set of elements is needed for extraction of 60 MeV protons. For extraction of 35 MeV protons the 1st electrostatic deflector can be removed from the vacuum chamber (see Fig. 4).

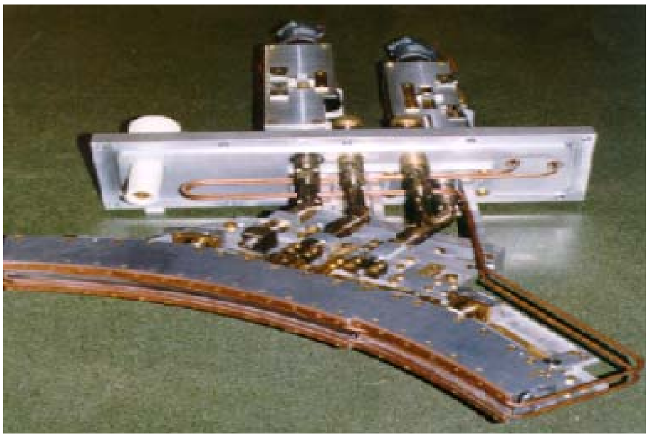

Fig. 3. Electrostatic deflector ESD-2-3: top view.

Electrostatic deflectors

The septum parts of the sections are water-cooled. The inlet part of the septum (thickness 0.1 mm) is made of tungsten. The high-voltage electrode (titanium) is not cooled by water, its entrance part is protected against beam particles by a special C-shaped diaphragm. The deflectors have a remote drive for radial moving and changing of the inclination angle in relation to the beam trajectory.

The gap between the septum and the high-voltage electrode is adjusted within the limits of 4÷15 mm without

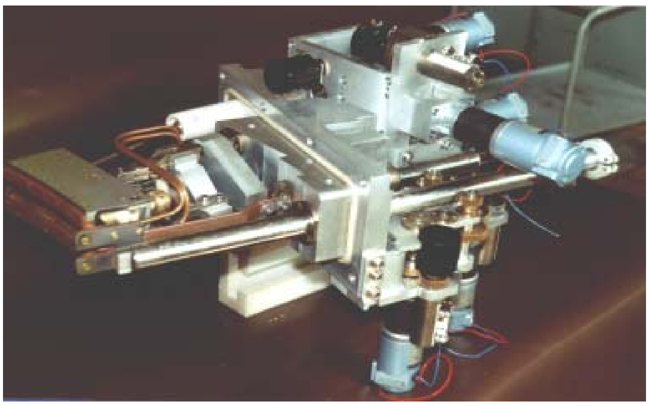

Fig. 4. Electrostatic deflector ESD-1.

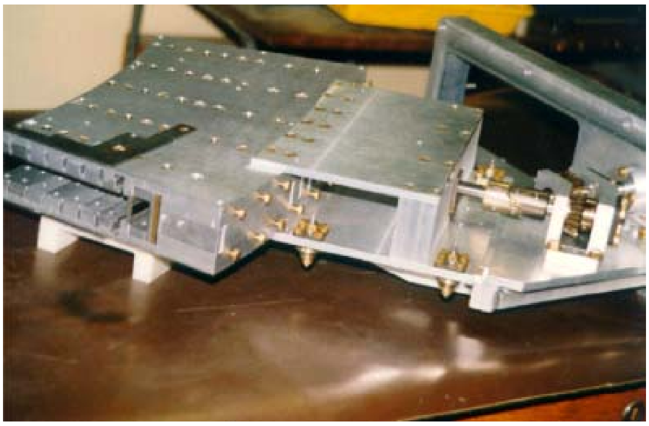

Fig. 5. Magnetic passive channel MC-2: entrance side.

opening the cyclotron chamber. Another adjustment of the gap can provide a variation of the gap within the limits of 10 mm along the beam trajectory.

Magnetic channels

The system of magnetic channels consists of three passive channels. In channel MC-1 the magnetic field is homogeneously decreased by ~0.18 T by means of steel plates with dimensions 2.5×30 mm^2. In channel MC-2 (see Fig. 5), the magnetic field is decreased by 0.18÷0.22 T and radial-focussing gradient 8 T/m is introduced by means of steel plates with dimensions $(2.5 \div 5) \times 50$ mm^2.

Additional steel plates in channels MC-1, 2 are placed in the aluminum C-shaped case to shim the magnetic field distortion caused by the channel in the region of the accelerated beam (the average magnetic field distortion and the first harmonic are shimmed down to several Gausses).

All magnetic channels have remote adjustment of their radial position in the chamber of the cyclotron. Channel MC-3 has also additional adjustment of its angular position [6].

The amplitude and the phase of the first harmonic of the magnetic field near the 60 cm radius are the parameters determining the characteristics of the beam turn separation enhancement in the electrostatic deflector mouth. The required characteristics of the first harmonic of the magnetic field ($B1 = 2$ G, $\varphi_1 = 0$) were shaped by means of the new cyclotron harmonic coils.

Conclusions

After upgrading, the AIC-144 isochronous cyclotron, designed and constructed at the Institute of Nuclear Physics in Kraków, is able to generate beams of protons (from 20 up to 60 MeV in current range of 10–100 μA), deutrons (15÷30 MeV, $I \cong 100$ μA) and α-particles (30÷60 MeV, $I \cong 30$ μA). During last 4 years it was successfully used for the production of some radioisotopes (see Table 2). In the future, we plan to use it generally for medical purpose (production of radioisotopes and ocular melanoma treatments).

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