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Warsaw cyclotron: present status and plans of development

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Abstract The operation of the Warsaw heavy ion cyclotron is presented. Technical solutions adopted were intended to accommodate the needs of different groups of users requiring a wide scope of beam species and energies. The accelerating structure of the machine, with two 45 degree dees, allows for the operation in the harmonics modes from 2 to 6 (first harmonic mode is also possible, although the acceleration of protons and deuterons is currently not within the scope of interest). Available energies range from 2 to about 10 MeV/amu due to the wide range of the stripping extraction system. Development of the multiturn stripping extraction technique was necessary to achieve the flexibility in energy variation, otherwise not reachable due to the highly saturated iron structure, which makes impossible the change of magnetic field and radio-frequency within the desirable limits. At present, the cyclotron, equipped with the ECR ion source, is capable of delivering ion beams from gaseous media up to Ar. Available ion beam species, their energies and intensities obtained up-to-date are shown. An overview of the experiments performed on the Warsaw cyclotron, including basic nuclear physics research, solid state physics and materials science, is intended to demonstrate the potential of the facility. The efficiency of the cyclotron and the ion beam line optics is discussed, as well as the plans for the future upgrade of the cyclotron and its infrastructure.

Key words accelerators physics • cyclotrons • application of cyclotron in nuclear • atomic and solid state physics

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Historical background

First plans to build a cyclic accelerator in Warsaw were drawn just after Lawrence made operational his first cyclotron in Berkeley. World War II cut short these ideas and only in 1972 the decision on building a heavy-ion accelerator in Warsaw was taken. It has been decided to choose a heavy-ion cyclotron similar to the Dubna U-200 machine. Soon after the raw iron magnet structure has been ordered in the Joint Institute for Nuclear Research (JINR) at Dubna, a small group of physicists and technicians performed preliminary shaping of the magnetic field [12]. This group, initially from the Physics Department of Warsaw University and the Institute of Nuclear Research, Świerk, became the "founding fathers" of the Heavy Ion Laboratory. The Laboratory was officially organized in 1979 as a joint venture of the Ministry of Education, the Polish Academy of Sciences and the National Atomic Energy Agency (PAA), administratively situated at Warsaw University. The laying of the cornerstone of the cyclotron building has unfortunately coincided with the beginning of the sharp economic crisis in Poland which practically stopped the progress of the project. Finally, in 1989 the cyclotron was installed in its site and from this time a real machine development begun. In November 1993, the first internal beam of – $^{20}\text{Ne}^{2+}$ ions – was obtained, and by the spring of 1994 ion beams of carbon, nitrogen, oxygen and neon were extracted. The overview of the early cyclotron operation is presented in [3]. With the accelerator running the attitude

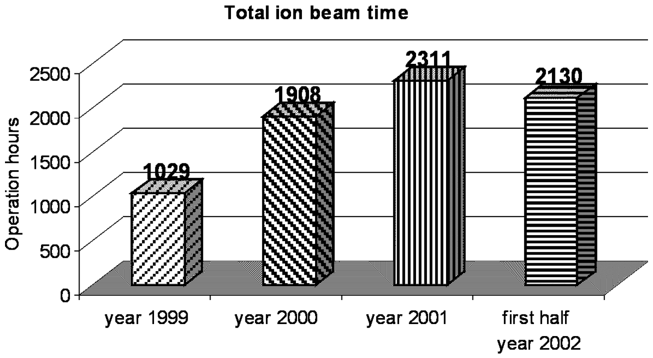

Fig. 1. Number of operation hours (beam-on-target) in the period from 1999 to the first half of 2002.

of the governmental financing agencies became more favorable, thus it became possible to build the experimental apparatus. First full-scale experiments started in 1996. Initially operating with an internal PIG ion source the machine was upgraded by the installation of the modern, home-made ECR ion source [10], which extended the range of available ion beams to argon (above the Coulomb barrier). Besides the continuous upgrades of the accelerator, substantial amount of beam time was delivered to the users – see Fig. 1.

Basic parameters of the U200-P cyclotron

Magnetic structure

The Warsaw cyclotron operates at high excitation currents – from 600 to 1200 A. The machine has two main coils, each of them consisting of 7 segments, connected in series. The main coils are cooled by demineralized water. The magnet iron is almost completely saturated, thus to obtain the required slopes a set of ten radial triple trim coils is used. As shown in Fig. 2, these coils are sufficient to introduce the necessary slope at the highest excitation currents or to offset an excess slope at the lowest current levels. The iron structure is shaped so that the ions with the ratio of atomic mass number to the charge state A/Q = 4 can be accelerated without any corrections.

Basic parameters of the magnetic structure

K range	90–160
Diameter of the magnet poles	200 cm
Max. excitation current	1400 A
Sectors	4 pairs
Sector gap in the center	41 mm
Min. sector gap (extraction radius = 85 cm)	26 mm
Valley gap	150 mm
Sector angle	42 deg
Max. mean magnetic field in the hill	2.7 T
Max. mean magnetic field in the valley	1.7 T
Trim coils, water cooled (demineralized water)	10 pairs
Current stability, main coils	10^{-4}
Max. current for trim coils	200 A
Current stability, correction coils	4×10^{-4}
Total weight of the main magnet	240 t

Accelerating structure

Number of dees	2
Angular range of dees	45 deg
Frequency range	12.3–18.4 MHz
RF generator frequency stability	$\sim 10^{-6}$
Maximum amplitude	75 kV
RF mode	pulsed
Duty factor	max. 60%
Harmonics	2 through 6
Quality-factor	5000–2000

Vacuum

Number of cryopumps	4
Final vacuum level	about 7×10^{-7} Torr
Continuous leakage	of the order of 2 mTorr l/s

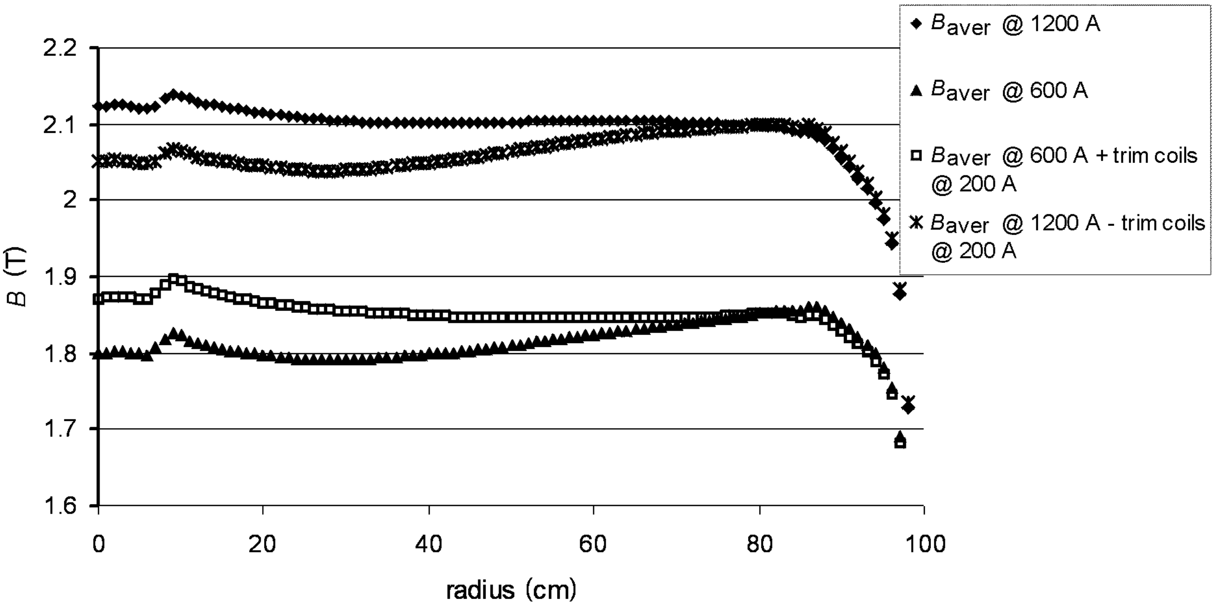

Fig. 2. Average (with respect to the azimuthal angle) magnetic field (B_{aver}) as a function of radius without and with the trim coils.

The cyclotron is equipped with an ECR ion source. The hexapole magnetic trap is built using permanent NdFeB magnets. The ion source operates at 10 GHz with the extraction voltage of 10 kV [10]. At present, the ion source provides beams of elements obtainable from gaseous media. The work to enlarge the scope of extractable beams – mainly metallic elements – is currently in progress. Details are presented in [10, 11].

The ions are injected into the cyclotron after a 90 degrees analyzing magnet, focusing optics, the sine wave buncher, and inflected to the horizontal plane by a mirror electrostatic inflector. A new, mechanically flexible cyclotron center has been designed and built to accommodate switching from the optics of internal PIG ion source to that of the external ECR ion source [6].

It was decided to use a two-gap buncher in the axial injection line. The principle of its operation is discussed in [8, 13]. The restriction that the accelerating voltage of the ECR ion source should be kept at the maximum value of 10 kV to facilitate bypassing of the elements of the center together with the fact that various charge states are used imposing a variable geometry of the buncher. The length of the drift-tube should be proportional to the product $\lambda\beta$, where λ is the RF wave length and β – the velocity of the particle, relative to the velocity of light. This product varies with particle and operating frequency, which makes the design very complex. Therefore, it was chosen to design a compromise fixed geometry for the first approach. The distance between the centers of the gaps was chosen equal to 41 mm and the aperture 50 mm. The length of the drift-tube corresponds approximately to particles with ratio around A/Q = 4. The experimental results in increasing the ion beam intensity are encouraging and justify the effort to design a final variable geometry buncher, which is under way. Detailed calculations and design are given in HIL Report [14], as well as the description of the appropriate RF-system. The first long-term operational test results gave a gain in intensity of 1.5 to 4 times depending on the ion beam species. Since then, the prototype buncher is routinely being used, but development work is going on.

The electrostatic mirror inflector is currently in use. The inevitable damage of the grid changes the initial conditions, therefore we have decided to introduce the correction mechanism by decoupling the upper and lower sections of some of the trim coils to provide vertical steering. This has been proved as an efficient way to offset the changes due to changing beam inflection conditions. Also, thermal deformation of the dees, if occurred, can be neutralized just by adjusting magnetic field structure.

The most important and the most time-consuming development done during the last few years was the general repair and reconstruction of the RF panel resonators [7]. Thanks to this action, the stability of the accelerating structure has been significantly improved with the duty factor being increased to over 60%.

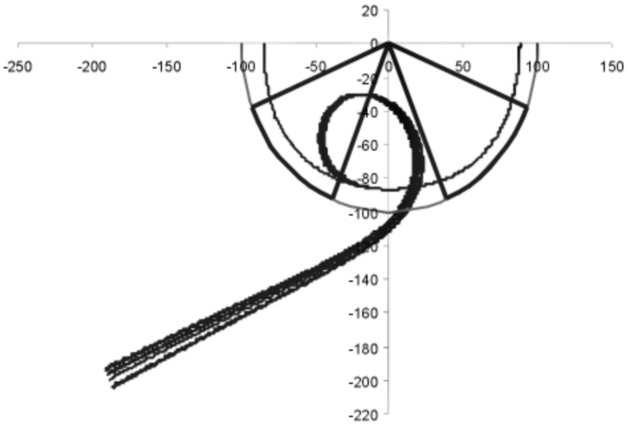

Fig. 3. Extraction of accelerated $^{14}N^{3+}$ ions stripped to the charge state 7+ from 83 cm radius. In this case optimum conditions are achieved. The extraction is by single turn and the passes through magnetic field boundaries are such that vertical motion is stable as shown in Fig. 4.

Multiturn stripping extraction of the low-energy ion beams

Two methods of ion beam extraction are commonly used to deliver external beams. One of them is electrostatic deflection, the application of high voltage to perturb the motion of accelerated ions by introducing the radial component of the momentum directed outwards. The other, used in our case, is the so-called stripping – insertion of a thin (of the order of few tens micrograms per square centimeter in this case, manufactured *in-situ* [9]) carbon or metallic foil in the chosen position. While the passage of accelerated ions through such foil does not cause any measurable energy loss, the effect is strong enough to inflict stripping of additional electrons [1]. Charge-to-mass ratio thus changes discretely and, as an effect, the radius of curvature of an orbit decreases. With the stripping foil inserted in the valley – an area of lowered magnetic field – and the stripping ratio (the final to initial charge ratio) of 2–2.5 the stripped ion will travel partly in the valley and partly in the hill, where the magnetic field is higher with respect to the valley by approximately 1 tesla. The net effect of the different radii of curvature in both regions is pushing the trajectory outwards, thus allowing the ion to leave the cyclotron chamber. By properly adjusting radial and azimuthal position of the stripper foil, the ions can be directed into the exit beamline, as shown in Fig. 3.

While electrostatic deflection is indispensable when running the highly charged ions – recharging by a factor of at least 2 is no longer possible – the stripping method is a simple way to extract low energy ion beams. One of the

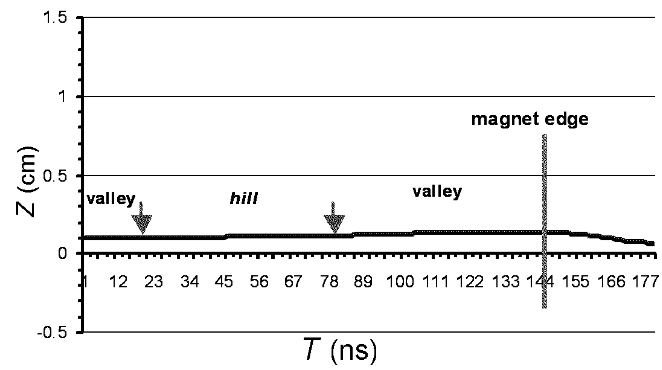

Fig. 4. Vertical motion of $^{14}N^{3+}$ ions stripped to $q = 7$. The arrows marked passages between the sector and valley, while the line corresponds to the edge of the main magnet.

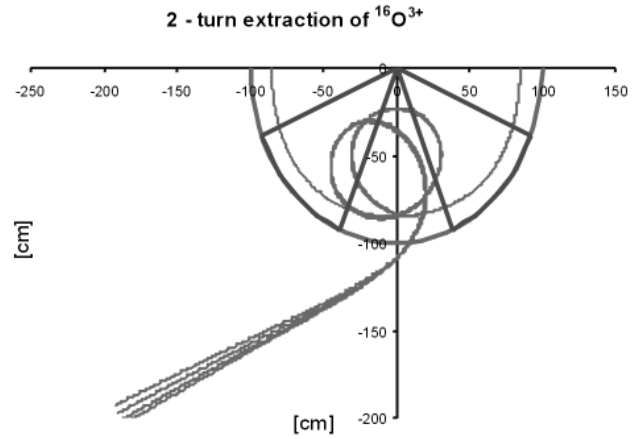

Fig. 5. Two-turn extraction of accelerated $^{16}O^{3+}$ ions stripped to the charge state 8+.

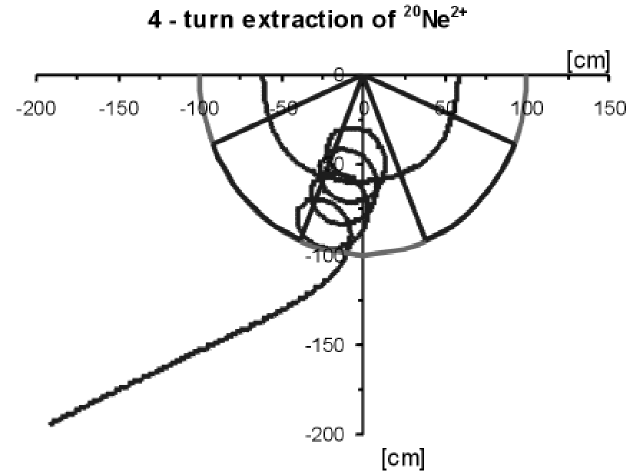

Fig. 7. The computer simulation of four-turn extraction of 0.6 MeV/amu $^{20}Ne^{2+}$ ions (58 cm extraction radius), successfully verified experimentally. Triangular contours represent the sectors. The position of the beamline corresponds to the lower left corner of the drawing.

obvious advantages of stripping is that the extracted beam travels the region of fringing field at the edge of the magnet at approximately right angle, thus the effect of strong radial defocusing is avoided. On the contrary the passage of electrostatically deflected beam through the fringing field requires the use of the system of magnetic focusing channels to prevent its loss.

The stripper for the U200-P cyclotron has been primarily designed to extract the ions recharged by a factor 2 to 2.5 from the radii in the range of 72–90 cm ([11] and references therein, [5, 12]). In such cases, a simple one-turn extraction is feasible. An apparent need for ions of energies lower than those resulting from accelerating ions up to the maximum radius forced us to test the possibility of extracting the ions from the orbits of radii much closer to the cyclotron center than the original stripper design assumed. One of the examples are Coulomb excitation experiments requiring the ion energies not exceeding the safe value of Coulomb barrier for a given projectile-target system (safe meaning low enough to assure non-intervention of the nuclear forces). Insertion of the stripper foil deeper into the cyclotron chamber causes the radius of curvature after the stripping to be too small to bring out the ions in a single turn. The same happens when stripping ratio exceeds 2.5, which is a common situation when accelerating small charge-to-mass ratio, low energy ions. To extract the low energy ions we have studied the possibility of multiturn extraction, a situation in which stripped ions travel outwards along the hill–valley edge making more than one turn in the process. Computer simulations of such modes of extraction were successfully verified on a number of beams [4]. Two- and three-turn extraction modes were tested in a number of cases. Switching from a simple, single-turn extraction to two (Fig. 5) or three turn mode assures a coarse variation of beam energy, while small changes of the extraction radius correlated with the proper azimuthal position of the stripping foil make fine tuning possible. The price to pay is that with more than one turn the beam is traveling in a strong field gradient between the sectors and valley usually no more at about 90° angle, which causes defocusing in the vertical direction. Figure 6 illustrates this effect. Combined with the effect of increased radial dispersion severe intensity losses are inevitable.

Perhaps the most spectacular result was obtained by extracting a 0.6 MeV/amu $^{20}Ne^{2+}$ ions, recharged to the 8+ state, from a 58 cm orbit, as shown in Fig. 7. Four-turn extraction achieved here is almost a model illustration of the principle of the method. It is worth noting that the nominal energy of $^{20}Ne^{2+}$ ions for the $K = 160$ machine is in the range of 1.6 MeV/amu, thus an almost threefold lowering of the energy has been achieved.

Concluding, the extraction by stripping has been proved to be a flexible method to obtain low energy ion beams

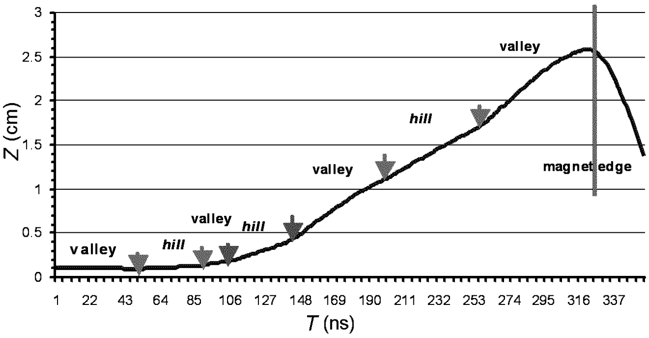

Fig. 6. Vertical motion of $^{16}O^{3+}$ ions stripped to $q = 8$. Similarly to the previous Fig. 4, the arrows marked passages between the sectors and valleys. It should be noted that in sharp contrast to Fig. 4 the vertical dispersion of the beam increased dramatically.

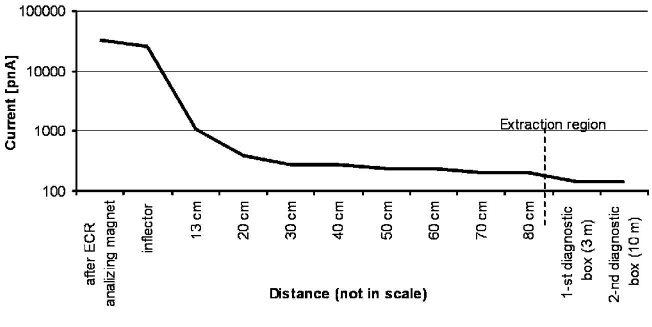

Fig. 8. Ion beam transmission profile without the buncher.

Ion	Energy (MeV)	Extracted current (pnA)	Charge after extraction	Extraction radius (cm)
$^{11}B^{2+}$	38–55	3–4	5	71–85
$^{12}C^{2+}$	22–48	2–20	5, 6	56–83
$^{14}N^{2+}$	28–42	13–22	6	69–84
$^{14}N^{3+}$	70–84	100–143	7	72–79
$^{16}O^{2+}$	32	5.7	7	79
$^{16}O^{3+}$	46–80	5.7–137.5	7, 8	63–83
$^{19}F^{3+}$	38–66	1.25	8	62–82
$^{20}Ne^{4+}$	70–120	11–35	9, 10	65–85
$^{20}Ne^{5+}$	140	40	10	73
$^{32}S^{5+}$	64–121.6	0.5–1.4	13, 14	62–85
$^{40}Ar^{7+}$	120–172	0.9–2.3	16–18	69–82

Table 1. Available ions beams and their intensities.

within a wide energy range. Multiturn stripping allows to overcome the limitations due to both too high stripping ratios and too low extraction radii for the usual single turn mode. This opens the opportunities for the groups from outside nuclear physics which often require much lower beam energies than those employed in basic nuclear physics investigations.

Ion beam transmission

The synthetic picture of the typical 1-turn-extracted beam transmission is shown in Fig. 8. Up to the inflector, a continuous ion beam is transported, while the sharp drop at first centimeters inside the cyclotron is due to switching to the RF pulsed mode, phasing of accelerated ions and the dispersion inflicted by the electrostatic inflector. It is foreseen that better matching of the emittance of the ion source and the acceptance of the cyclotron will further improve the transmission to the first orbits (studies in progress). Another factor is the relatively poor vacuum in the central region of the cyclotron still giving a field of improvement. While, at present, not possible to be measured precisely, this poor quality of the vacuum can be ascertained by the observed glow discharges in the neighborhood of the inflector. From 25 cm on, the losses of the ion beam intensity are acceptable and explainable by the losses on the residual gas of the order of 1×10^{-6} Torr [2]. Extraction of the beam (83 cm in Fig. 8) causes a relatively small effect, showing high stripper efficiency. The measured ion beam intensity between the first and the second diagnostic points on the beam line does not change and, irrespective of the line used, the transmission remains close to 100% to the user-installed scattering chamber system. It is, however, to be remembered that this situation corresponds to 1-turn-extraction conditions and may deteriorate for the multi-turn-extracted beams as discussed above.

Available ion beams, energies and intensities

Table 1 shows the parameters of selected ion beams requested by the users and delivered by the cyclotron. The range of the intensities offered is primarily due to the requirements of experimental set-ups (detector efficiency, data acquisition systems etc.). Some limitations occur which are connected to the geometrical conditions of beam extraction at different energies, as was discussed above.

Ion beam lines and experiments

A schematic view of the experimental hall is presented in Fig. 9. Lines C1, C2, C3 and C4 are used by permanent experimental set-ups, while lines B and D accommodate the needs of the users having their own, dedicated chambers.

Examples of experiments employing heavy ions beams from the cyclotron include:

1. Investigation of the high spin states of nuclei, with the multidetector OSIRIS II system. The experimental set-up consists of 10 anticompton shielded HPGe detectors equipped with a charged particle 4π multiplicity filter Si-Ball, a 50 element BGO γ-ray multiplicity filter and a 4 sector HPGe polarimeter (line C3).

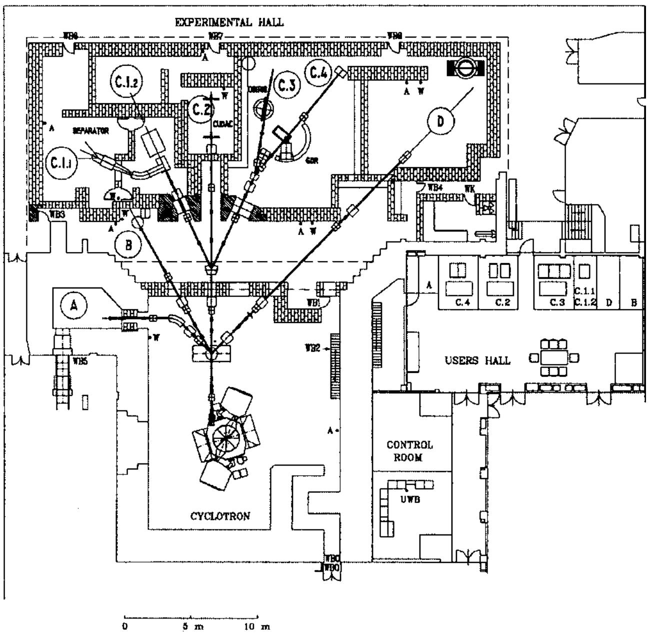

Fig. 9. Schematic view of the experimental area.

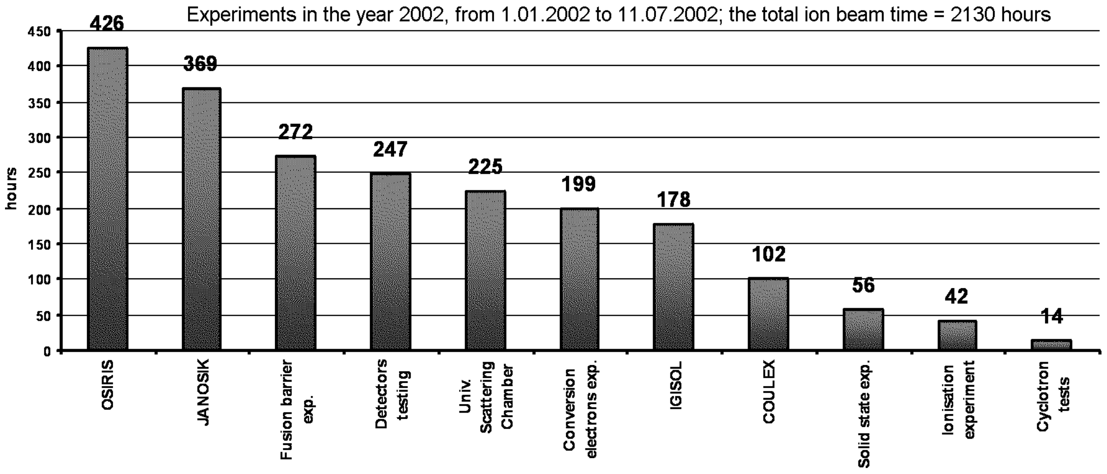

Fig. 10. Experiments performed from 01.01.2002 till 11.07.2002.

2. Coulomb Excitation (COULEX) studies. A permanent set-up for such investigations, consisting of an array of PIN-diodes (CUDAC – Coulomb Universal Detector Scattering Chamber) in connection with the computer data analysis package GOSIA, maintained by the Laboratory, attracts scientists from many institutions (line C2). The same set-up is used for the investigation of fusion barriers via detection of scattered projectiles.
3. Investigation of the reaction products by means of the on-line mass separator with ion-guide system, IGISOL now in test phase. The system uses the Scandinavian-type mass separator built in the Institute for Nuclear Studies, Świerk (line C1).
4. Reaction studies of the light nuclei using universal large scattering chamber at line B equipped with the charged particles detectors (a gas filled ionization counter as well as semiconductor detectors).
5. Giant Dipole Resonance studies using experimental set-up JANOSIK developed for the detection of high-energy photons emitted in heavy-ion collisions. The set-up consists of a large NaI(Tl) detector (25 cm × 29 cm) surrounded by shields: a passive lead shield, an active anticoincidence plastic shield and an LiH shield to absorb neutrons, and a multiplicity filter of 32 small scintillator detectors (BaF_2 and NaI(Tl)) (line C4).
6. Applications of heavy ion beams in solid state physics (internal or extracted beams).
7. Investigation of the ion–atom collision processes by X-ray spectroscopy using the Si(Li) detector (lines B or D). The scientific interest is concentrated in:
   a) studies of the X-ray emission from swift heavy projectiles slowing down in thin target foils and
   b) studies of the multiple ionization effect through the measurement of the L- and M-shells X-ray production cross section, X-ray shift and line broadening induced by heavy ions in selected heavy elements.

The histogram of the beam time for different projects (first half of 2002) is presented in Fig. 10.

Plans of development

Depending on the financial condition of the Laboratory during the next few years, the following major upgrades of the machine and its infrastructure are foreseen (Table 2).

Summary

This paper presents in a very short form the status of the Warsaw cyclotron. Beside the cyclotron development – resulting in the improvement of the reliability of the facility – the Laboratory staff is also involved in the basic research at home as well as in international collaborations and uses other European research facilities. Full and detailed information can be found in HIL Annual Reports and in the number of Laboratory Internal Reports available on request from the Laboratory.

Acknowledgments The material presented in this paper is a compilation of the work performed by the whole HIL crew. Special thanks are due to the technical staff in charge of the cyclotron maintenance and operations. Fruitful discussions with the users and their help in preparing the manuscript are

Table 2. Near future development plans.

	Estimated completion time
Cyclotron	
Cyclotron upgrade	
improvement of phase and amplitude stability	2003
precise beam energy definition using time-of-flight method	2003
final version of the computerized remote control system	2004
ECR ion source	
Upgrade of the source	
computerized remote control system	2003
oven for production metallic ions	2003
Second ECR ion source	funding–dependent
Injection line for the second ECR ion source	funding–dependent

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