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CRYOGENIC SOURCES OF IRRADIATION

ABSTRACT *In the paper are described cryogenic sources of irradiation, basing on the case of large accelerator system of the Nuclotron, built in JINR in Dubna, Russia. In this device beams of light ions, protons and of heavy ions are accelerated, while their collisions with appropriate targets allow for investigation various nuclear reactions, improving in this way our basic knowledge. On the other side ions irradiation is more and more useful now in medical applications, in therapy of the oncology diseases, especially at anti-cancer therapy. This topic is considered in the paper in more details basing on future, perspective program of using Nuclotron at this aim.*

Keywords: *irradiation, radiotherapy, accelerator, superconductivity*

1. INTRODUCTION

Too intensive UV light irradiation may be danger for human skin and finally can lead to illnesses, even cancer. There are various medical methods of treatment against this disease, for instance using photons beam irradiation.

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In the paper is presented other perspective method, which can be useful in medicine, of using irradiation generated in cryogenic accelerators, for treatment just against the cancer. Generally accelerators are used for studying nuclear physical reactions, in the processes of the bombardment by ions beam the target formed from various nuclei as Au and looking then for its disintegration or other effects. It has essential meaning from scientific point of view but as it will be shown in the paper beam irradiation, can be utilized also in medicine. To description of the possibility of application irradiation generated in the nuclear superconducting accelerator, which is Nuclotron working in the Laboratory of High Energies Physics in Dubna [1-5], Russia, in oncologic diseases therapy as anti-cancer is devoted present paper.

2. APPLICATION OF CRYOGENIC ACCELERATORS IRRADIATION IN ONCOLOGIC THERAPY

Irradiation created in the cryogenic accelerators such as Nuclotron, constructed from superconducting electromagnets, beside of using in basic sciences for investigations nuclear reactions, can be useful in applied research too. It concerns especially medical applications and also for instance space research, for testing an endurance of electronic computer chips and processors used in space crafts, against cosmic irradiation. Endurance of electronic elements against irradiation is very important problem, may be responsible for some failures or at least disturbances in the work of expensive cosmic probes. One of such accidents has happened quite recently. In the paper are presented advantages of using ions irradiation generated in the cryogenic, superconducting accelerators, as for instance Nuclotron in oncologic therapy. Actually medicine has three methods of struggle against oncologic diseases: surgery, chemotherapy, radiotherapy. For radiotherapy of oncologic diseases application of various nuclear physics devices as linear accelerators, cyclotrons, and synchrotrons is possible. Each type of the accelerators has an advantages and disadvantages at its clinical use.

Since 1954 various centers of the proton and ion therapy have been established. Historically firstly it was applied the proton beam therapy. As of June 2011, there were a total of 37 proton therapy centers in Canada, China, England, France, Germany, Italy, Japan, Korea, Poland, Russia, South Africa, Sweden, Switzerland, and USA; and more than 73800 patients have been treated. One hindrance to universal use of the proton in cancer treatment is the size and cost of the cyclotron or synchrotron equipment necessary. Several industrial teams are working on development of comparatively small accelerator systems to deliver the proton therapy to patients. Among the technologies being investigated are Superconducting synchrocyclotrons (also known as FM Cyclotrons), ultra-compact Synchrotrons and Dielectric wall accelerators.

Heavy ion therapy is the use of particles more massive than protons or neutrons, such as carbon ions. Compared to protons, carbon ions have an advantage: due to the higher density of ionization at the end of their range, correlated damages of the DNA structure within one cell occur more often so that it becomes more difficult for the cancerous cell to repair the damage. This increases the biological efficiency of the dose by a factor between 1,5 and 3. In contradiction to protons, carbon ions have the disadvantage that beyond the Bragg peak, the dose does not decrease to zero, since nuclear reactions between the carbon ions and the atoms of the tissue lead to production of lighter ions which have a higher range. Therefore, some damage occurs also beyond the Bragg peak. By the end of 2008, more than 5000 patients have been treated using carbon ions.

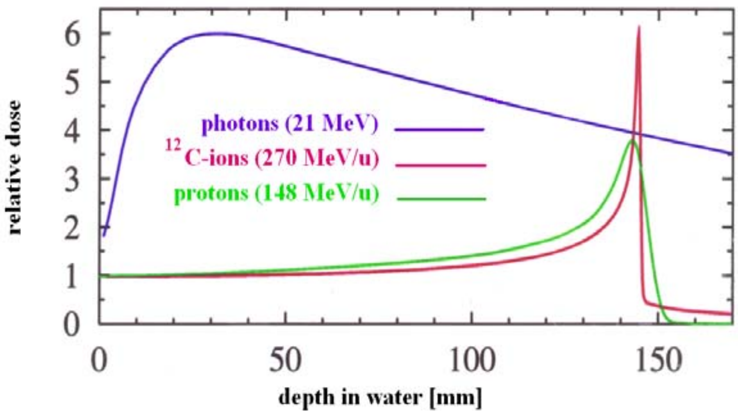

Fig. 1. Relative dose of irradiation versus depth inside water medium, for photons, protons and carbons ions

At the end of 2008, only two centers using carbon ions are in operation, both in Japan: the HIMAC at Chiba and the HIBMC at Hyogo. In Germany, treatment at the GSI in Darmstadt, which is primarily a physics laboratory, has been discontinued in 2008, but the new one center HIT in Heidelberg, which is a dedicated facility, started in November 2009. The CNAO in Pavia, Italy is going to open now and will be one of the most advanced centers for particle therapy with hadrons. In Russia two clinical-physical complexes of beam therapy operate in the DLNP JINR (Dzelepov Laboratory of Nuclear Problems in Joint Institute for Nuclear Research) at Dubna and ITEP (Inst. Theoretical and Experimental Physics) in Moscow for more than thirty years. Significant experience and successful results of proton therapy have confirmed that this kind of treatment is promising due to that it differs by the high degree of conformity and especially minimal irradiation dose of a healthy tissue, unlike the one using electronic and photon beams. Advantages of using ions therapy irradiation in oncologic diseases in comparison to the lasers – photons beam are visible in Figures 1-2. In Figure 1 is seen comparison of the dose of irradiation in relative units versus depth inside given medium for the laser irradiation, protons and carbon ions. As it follows from Figure 1 shape of this relation is very broad for laser beam, while in the case of protons and carbon ions the corresponding Bragg peak is much sharper and localized on well determined depth inside the medium – water. In Figure 2 is shown on the other hand the comparison of the broadening of these beams versus depth inside water. Also in this case is well observed an advantage of using carbon ions irradiation in comparison to photons and protons beam. However for depth larger than 70 mm, proton beam undergoes more strongly the broadening effects than photons. Especially attractive from the point of view of broadening the beam is using therefore the carbon ions irradiation, instead of protons presently most frequently applied.

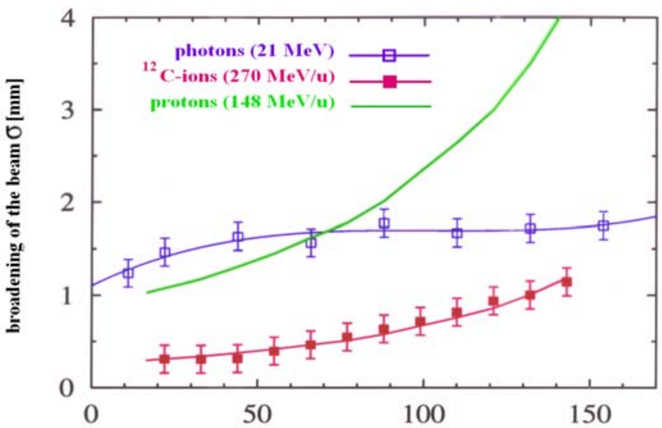

Fig. 2. Broadening of the irradiating beam versus depth inside water in mm for various kinds of irradiation

TABLE 1
Values of the beam intensities required for the treatment of patient

	Proton	Ion				
		C	N	O	Ne	Ar
Beam intensity on target (particle/second)	$1{\times}10^{11}$	$1{\times}10^{9}$	$9{\times}10^{8}$	$7{\times}10^{8}$	$5{\times}10^{8}$	$2{\times}10^{8}$

One more advantage of the ^{12}C therapy consists in that during the irradiation, isotopes of carbon ^{10}C and ^{11}C are created. Emitted then positron can be easily registered from the outside. Using of such modified the positron – – emission tomography (PET) allows to carry out exact monitoring of distribution of primary ions of carbon and directly to compare during a medical session the received doze of irradiation with planned.

The energy and intensity of beams for hadron therapy are known today: energy of protons up to 250 MeV/nucleon, energy of ions ^{12}C 500 MeV/nucleon, while beam intensity for these and others used ions are given in Table 1. As it follows at present the radiating oncology and medical-biologic investigations start to be also carried out on the light ions beams, such as C, N, O, Ne, Ar, especially because lighter ions penetrate more effectively into given tissue, as indicates Figure 3. It is shown here comparison of the ions kinetic energy necessary for oncology therapy versus depth of penetration of beam for various nuclei. For assuring the strictly controllable doze selectively injection on required depth the beam energy should be adjustable within the limits of 80-500 MeV/nucleon. For the majority of existing projects with carbon beams with using the synchrotron or cyclotron the necessary energy of an ionic beam of carbon (430-450 MeV/nucleon) is practically unattainable.

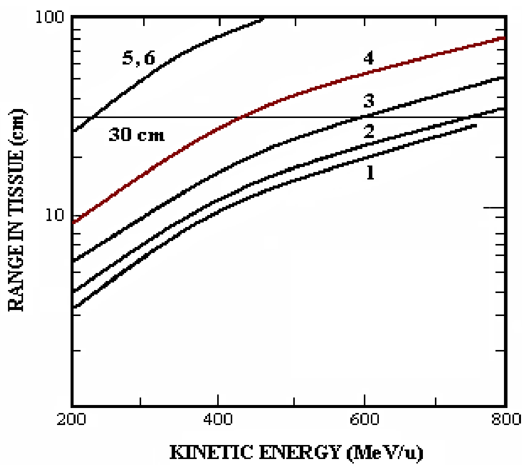

Fig. 3. Required ions kinetic energy for oncology therapy versus depth of penetration of beam for various nuclei:
1) Argon (Z = 18, A = 40),
2) Silicon (Z = 14, A = 28),
3) Neon (Z = 10, A = 20),
4) Carbon (Z = 6, A = 12),
5) Helium (Z = 2, A = 4),
6) Protons (Z = 1, A = 1).
Z – charge, A – atomic mass

3. CRYOGENIC ACCELERATOR WITH SUPER-CONDUCTING ELECTROMAGNETS – NUCLOTRON

The accelerator has doubtless advantage in the case of use of superconductivity. The superconducting magnets in comparison with the "warm" magnets, working at an ambient medium temperature, have a number of advantages, concerning the operating expenses, most of which are due to the cost of electrical energy, which are greatly lowered. Also the capitals required for building magnets systems on the base of superconductivity and the metal content are significantly reduced. Large decrease in size of the magnet systems allows practically all their elements to be prepared at simple machine tools.

To establish the hadrons' therapy center on the basis of the accelerator similar to the Nuclotron, is a competitive issue, as in JINR Dubna already is successfully operating prototypes of the basic elements: superconducting synchrotron – the Nuclotron, shown in Figure 4, as well as ion source with an electronic string on the basis of the superconducting solenoid [6]. The Nuclotron perimeter is about 250 meter. Basic elements of the ring are: 96 superconducting dipole magnets each 1,5 meter long, storing energy of 19,8 kJ and 64 quadrupole magnets each 0,45 meter long, of energy 6,9 kJ [1-5]. The cryogenic supply system is based on three industrial helium refrigerators/liquefiers KGU – 1600/4.5 with a total capacity of 4,8 kW at 4.5 K. During the production of the accelerated carbon ions the superconducting magnets are used also outside of the accelerator – in the ions source, first element of an accelerating complex, which defines features, parameters, efficiency and possibilities of accelerator.

Fig. 4. View of the Nuclotron ring with superconducting electromagnets

In Nuclotron cryogenic electron beam ion source (EBIS) is used. Typically, these ion sources (EBIS) are used in a "direct beam" mode of operation in order to produce highly charged ions (bare nuclei of heavy elements in a limiting case).

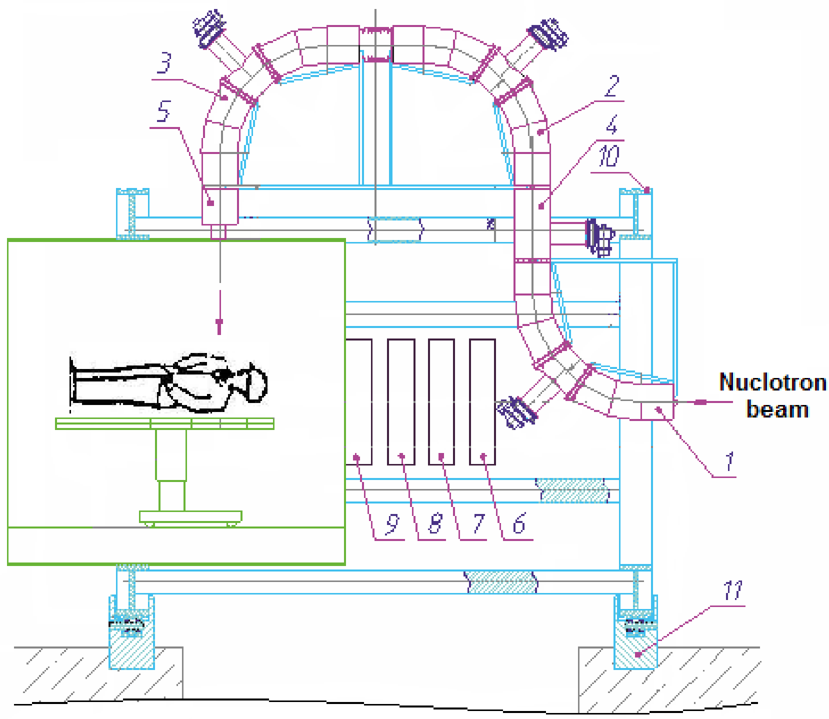

Fig. 5. Scheme of gantry project with superconducting magnets and cold heads cryocoolers: 1, 2, 3 – dipole magnets; 4 – focusing magnet; 5 – scanning magnet; 6 – sealing of helium tube; 7 – sealing of vacuum tube; 8 – electric siding connection; 9 – electric siding connection of cold head valves; 10 – frame of gantry; 11 – support of frame wheels

The dense electron beams of about 1 m long and of about 1 mm cross section diameter are confined in EBIS-es by the strong longitudinal magnetic field of superconducting solenoids. On the other hand, the electron beam space charged confines the injected low-charge state ions during an arbitrary confinement time necessary to produce definite highly charged ions by the beam electron impact. After that the obtained highly charged ions can be extracted from the source and applied for further acceleration in synchrotrons for basic or applied research. In JINR the system of the beam rotation (project gantry) with superconducting magnets, allowing to irradiate tumor of the motionless patient from different sides is developed for treatment of oncologic diseases by an irradiation with multi charged ions of carbon with energy of 460 MeV/u. Application of the superconductivity of magnets allows to decrease the gantry weight for carbon ions from several hundreds tons to sizes less than 10 tons that does the project reliably sold, and the gantry mechanism manageable. The gantry shown in Figure 5 contains three identical superconducting dipole magnets, superconducting focusing magnet and warm scanning magnet. The basic parameters of dipole magnets: the induction 6 T, 80 mm internal diameter of winding, 1 m radius of bend of the magnet, 90° rotation angle of beam.

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KRIOGENICZNE ŹRÓDŁA NAPROMIENIOWANIA

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SRESZCZENIE *Przedstawiono kriogeniczne żródła napromieniowania, w oparciu o układ nadprzewodnikowego akceleratora jonów Nuklotronu, zbudowanego w ZIBJ w Dubnie, w Rosji. Akcelerator ten umożliwia napromieniowanie jonami i jest używany generalnie do badań reakcji jądrowych. Z drugiej strony, naświetlanie jonami, w projekcie gantry, odgrywać może coraz większą rolę w onkologii przy leczeniu nowotworów, np. w przypadku zbyt głębokiego dla terapii laserowej położenia nowotworu lub bliskości innych organów.*

Słowa kluczowe: *promieniowanie, radioterapia, akcelerator, nadprzewodnictwo*

Prof. Jacek SOSNOWSKI, D.Sc., hab. is absolvent of the Warsaw University, Physics Faculty. His Ph.D. theses were devoted to the investigations of the superconductivity in semiconducting lanthanum selenide, while habilitation was devoted to the investigations of superconductivity in A15 structure Nb_3Ga alloys with magnetic 3d impurities. In 2007 year he was nominated with the title of full professor in technical sciences. Since 1980 year he works in Electrotechnical Institute in Warsaw on applied superconductivity subject and published in this field more than 200 scientific papers. He has undergone various scientific scholarships in French, Russia, Japan, Germany. Recently he joined JINR in Dubna, in Russia.

Yulia MITROFANOVA, M.Sc. Eng., Ph.D. student – in 2001 she finished the Moscow Power Engineering Institute, Department of nuclear stations//installations and thermonuclear synthesis. Now she is research fellow, chief of group at the Laboratory of High Energies of Joint Institute for Nuclear Research. Main research direction is designing of helium cryogenic system for the new accelerating complex of laboratory (booster/synchrotron/collider); development of the recondesation system of nitrogen for this complex; computer simulation of thermo dynamical cycles of the corresponding cryogenic equipment. During the Nuclotron (superconducting accelerator) run she is a chief of the operating team: preparation of cryogenic installation for the session of accelerator and participation in it, personnel training. The results of scientific activity are published in 10 publications.

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