# DEVELOMPENT OF ACCELERATORS AND DETECTOR SYSTEMS FOR RADIACIAN MEDICINE IN DLNP JINR

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*Abstract*

The DLNP JINR activity is aimed at developing two directions in radiation medicine: development of accelerator technique for proton and carbon treatment of tumors and new types of detector systems for spectrometric computed tomography (CT) and combined magnetic resonance tomography (MRT)/positron emission tomography (PET).

JINR-IBA realized the development and construction of proton medical cyclotron C235-V3. At present time all basic cyclotron systems were constructed. During 2011 we plan to assemble this cyclotron in JINR and in 2012 perform tests with extracted proton beam.

A superconducting isochronous cyclotron C400 has been designed by IBA-JINR collaboration. This cyclotron will be used for radiotherapy with proton, helium and carbon ions. The $^{12}C^{6+}$and $^{4}He^{2+}$ ions will be accelerated to the energy of 400 MeV/amu, the protons will be extracted at the energy 265 MeV. The C400 construction was started in 2010 in frame work of the Archarde project (France).

Modern CT require modification to allow determining not only density of a substance from the X-ray absorption coefficient but also its chemical composition (development of spectrometric CT tomographs with colored X-ray imaging). JINR develops the principle new pixel detector systems for the spectrometric CT. A combined MRT/PET is of considerable interest for medicine, but is cannot be made with the existing PET tomographs based on detectors of compact photomultipliers. Change-over to detectors of micropixel avalanche photodiodes (MAPDs) developed in JINR allows making a combined PET/MRT .

## PROTON THERAPY

Dubna is one of the leading proton therapy research centers of the in Russia [1]. The modern technique of 3D conformal proton radiotherapy was first effectuated in Russia in this center, and now it is effectively used in regular treatment sessions [1-2]. A special Medico-Technical Complex was created at JINR on the basis of the synchrocyclotron (phasotron) used for proton treatment. About 100 patients undergo a course of fractionated treatment here every year. During last 10 yeas were treated by proton beams about 660 patients .

## PROTON CYCLOTRON C235-V3

A cyclotron C235–V3, superior in its parameters to the medical proton cyclotron IBA C235 installed in 10 proton treatment centers of the world, has been design and manufactures by JINR-IBA collaboration. This cyclotron design is an essentially modified version of IBA C235 cyclotron [3-4] (Table 2).

Table 2 JINR-IBA cyclotron C235-V3

| Parameter | C235 | C235-V3 |
|---|---|---|
| Optimization of magnetic field at modification of sector | | Modification of sector azimuthal angle at R>80 |
| Vertical betatron frequency at R>80 | Qz=0,25 | Qz=0,45 |
| Vertical coherent beam displacement related to median plate effects | 6-7 mm | 1,5-2 mm |
| Beam losses at proton acceleration | 50% | 15% |
| Beam losses at extraction | 50% | 25% |
| Reduction of radiation dose of cyclotron elements | | by 2-3 times |

The one goal is to modify the sectors spiral angle at R>80 cm for improving of the cyclotron working diagram (Fig.1) and reduction of coherent beam losses at acceleration. The coherent beam displacement z from median plane is defined by vertical betatron tune $Q_z$: $z \propto Q_z^{-2}$. At $Q_z \approx 0.2$ the coherent beam displacement corresponds to 7 mm and at amplitude of free axial oscillations of 2-3 mm can became to beam losses at reduction of the sector gup in the C235-V3 cyclotron. An increase of vertical betatron tune from $Q_z \approx 0.2$-$0.25$ to $Q_z \approx 0.4$ in C235-V3 permits to reduce by 3-4 times the coherent losses at proton acceleration (Table 2).

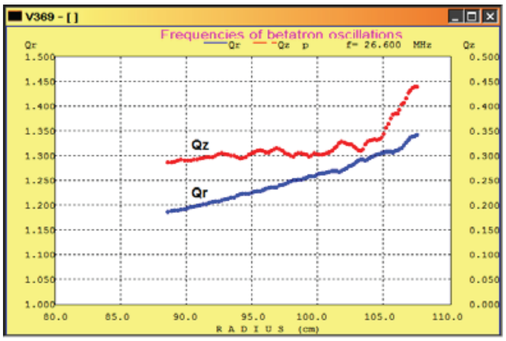


Figure.1: Dependence of betatron tunes on radius in cyclotron C235-V3.

The modification of extraction system is other aim of new cyclotron C235-V3 [4]. The main peculiarity of the cyclotron extraction system is rather small gap (9 mm) between sectors in this area. The septum surface consists of several parts of circumferences of different radii. The septum thickness is linearly increased from 0.1 mm at entrance to 3 mm at exit. The proton extraction losses essentially depend on septum geometry. In proposed JINR septum geometry when minimum of septum thinness is placed on a distance of 10 cm at entrance the losses were reduced from 25% to 8%. Together with an optimization of deflector entrance and exit positions it leads to increasing of extraction efficiency up 80%. The new extraction system was constructed and tested on IBA cyclotron C235. The experimentally measured extraction efficiency was improved from 60% for old system to 77% for new one (Fig.2).

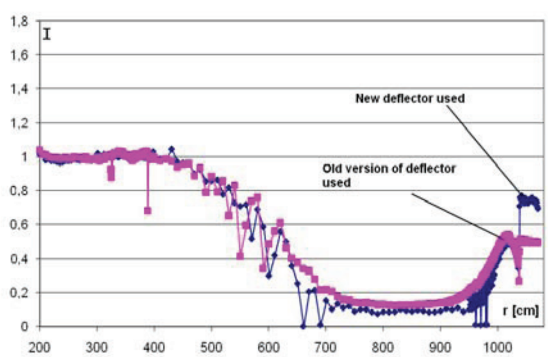


Figure 2: Proton beam extraction in cyclotron C235 with old IBA deflector and new electrostatic deflector developed in JINR.

Advantages of the medical proton cyclotron are simplicity, reliability, small size, and most importantly, the ability to modulate rapidly and accurately the proton beam current (Fig.3). The current modulation of the extracted proton beam at a frequency up to 1 kHz [5] is most advantageous with Pencil Beam Scanning and Intensity Modulated Proton Therapy. The energy of the extracted beam in cyclotron is fixed. However the fast proton energy variation at a rate of 15 MeV/s is easily performed during active cancer treatment by using a wedge degrader. This energy variation rate is few times faster than for typical synchrotron regime.

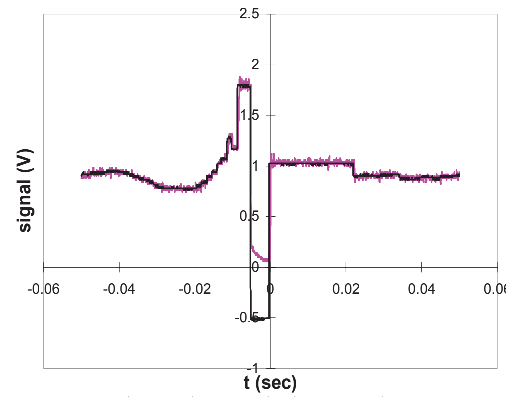


Figure.3: Beam intensity variation at the IBA C235 proton cyclotron.

## SUPECONDUCTING CYCLOTRON C400 APPLIED FOR CARBON THERAPY

Carbon therapy is the most effective method to treat the resistant tumors. A compact superconducting isochronous cyclotron C400 (Fig.4) was designed by JINR-IBA collaboration (Table 3) [4-8]. This cyclotron will be used for radiotherapy with protons, helium and carbon ions. The $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to the energy of 400 MeV/amu and $H_2^+$ ions will be accelerated to the energy 265 MeV/amu and protons will be extracted by stripping.

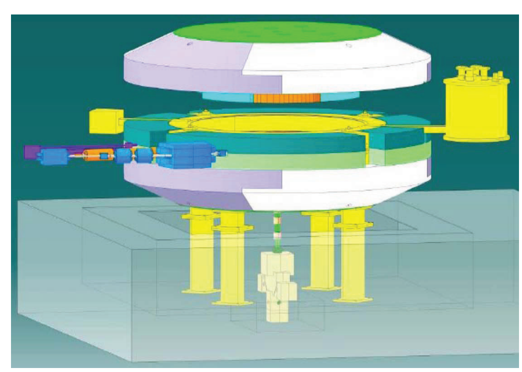

Figure. 4: Common view of C400 cyclotron.

Table 3: Main parameters of the C400 cyclotron

| | |
|---|---|
| General properties | |
| accelerated particles | $H_2^+$, $^4He^{2+}$, $^6Li^{3+}$, $^{10}B^{5+}$, $^{12}C^{6+}$ |
| Injection energy | 25 keV/Z |
| Final energy of ions, Protons | 400 MeV/amu 265 MeV |
| Extraction efficiency | ~70 % ( by deflector) |
| Number of turns | ~1700 |
| Magnetic system | |
| Total weight | 700 tons |
| Outer diameter | 6.6 m |
| Height | 3.4 m |
| Pole radius | 1.87 m |
| Valley depth | 60 cm |
| Bending limit | K = 1600 |
| Hill field | 4.5 T |
| Valley field | 2.45 T |
| RF system | |
| Radial dimension | 187 cm |
| Vertical dimension | 116 cm |
| Frequency | 75 MHz |
| Operation | 4 harmonic |
| Number of dees | 2 |
| Dee voltage: center extraction | 80 kV 170 kV |

## DETEECTORS FOR TOMOGRAPHY

The developed spectrometric CT tomographs of next generation should measure not only density of a substance but also its chemical composition. Colored X-ray imaging CT will ensure high-contrast imaging of a structure with different chemical compositions (tomography at different gamma ray energies selected near the K-edge of absorption lines of such elements as Ca, C, Fe, etc.) allowing, for example, clear-cut image of blood vessels including those behind bone structures with considerable shadowing of these structures. The gamma ray energy in the spectral CT tomography based on the JINR-TSU GaAs pixel detector [9] is determined by a special chip involving a comparator of eight signal levels (eight colors) that allows spectrometry and determination of gamma ray energy from this information thus implementing colored X-ray imaging. The detecting systems of the spectrometric CT tomography are based on the semiconducting heterostructures. Together with spectrometric possibilities the pixel detectors on basis of GaAs(Cr) have a high space resolution(~100 μm), their sensitivity is one order of magnitude better comparing with Si detectors at photon energy of 30-35 kev.

A combined MRT/PET tomograph is under consideration in many research centres. The application of micropixel avalanche photodiodes (MAPDs) allows making a combined PET/MRT tomograph. This photodiode [11] consists of many microcells, micropixels, each working in the yes/no Geiger mode with a high internal gain (up to $10^5$) and being capable of detecting single photons. A special shop for assembly and testing of micropixel detectors is built at JINR. MAPDs are more and more widely used in nanoindustry (laser location, optical-fiber communication, optical information transmission lines, systems for optical readout of super high-density information from various carriers on the nanostructure basis, luminescence of quantum dots) and in development of medical diagnosis equipment (PET, combined PET/MRT, single-photon emission tomograph). The MAPD advantages comparing with photomultipliers [10] are high dynamic range (pixel densities of up to $4\times10^4$ $mm^2$); photon detection efficiency up to 30%; gain up $10^5$; insensitivity to magnetic field; better radiation hardness; compact and rigid; low voltage supply (<100 V).

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