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UPDATED STATUS OF PROTOM SYNCHROTRONS FOR RADIATION THERAPY

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Abstract

Physical-Technical Center of P.N. Lebedev Physical Institute of RAS and Protom Ltd. are engaged in development and implantation of synchrotrons for proton therapy into clinical practice. There are two proton therapy complexes “Prometheus” in Russia. That are fully developed and manufactured at Physical-Technical Center and Protom. Every day patients with head and neck cancer get treatment using "Prometheus" at the A. Tsyb Medical Radiological Research Center. At the moment these facilities together have accumulated more than 5 years of clinical experience. Two facilities are based on the Protom synchrotrons in the USA. One operates at the McLaren Hospital PT Center, it started to treat patients in 2018. Another one is as a part of the single-room proton therapy system “Radiance330” in Massachusetts General Hospital that went into clinical operations in 2020. The first Israel proton therapy complex based on Protom synchrotron was launched in 2019. Protom facilities provide full stack of modern proton therapy technologies such as IMPT and pencil beam scanning. Key features of Protom synchrotron: low weight, compact size and low power consumption allow it to be placed in conventional hospitals without construction of any special infrastructure.

This report presents current data on accelerator researches and developments of Physical-Technical Center and Protom Ltd. In addition, it provides data on the use of Protom based proton therapy complexes under the clinical conditions.

INTRODUCTION

Proton therapy (PT) is one of the most accurate and modern methods of radiotherapy and radiosurgery. [1, 2]. Protons can reduce the radiation load on surrounding tissues up to 30-50% in comparison with gamma rays. The use of a proton beam for tumors located near critical organs, such as the brain stem, optic nerves, etc. are particularly effective. Therefore, in cases of head and neck cancer, proton therapy is the most advantageous of the available types of treatment for many patients. Given the advantages of this type of treatment over radiation therapy, using gamma radiation and electron beams, proton therapy is increasingly being used in the treatment of cancer. There is an increase of PT centers around the world.

In the world, active work is being carried out aimed at increasing the accuracy of dose delivery to the tumor, reducing the time that patients stay under the influence of radiation and increasing the availability of this method for a larger range of patients. New proton accelerators, as well as more cost-effective and accurate immobilization systems for patients are being developed for these purposes [3].

Protom Ltd. is a manufacturer of the equipment for Proton Therapy (PT). Protom can provide full range of the technologies for PT including the accelerator complex based on the compact synchrotron, pencil beam scanning beam delivery system, patient positioning and immobilization system, treatment planning system and all needed software. The Protom synchrotron [4,5] – one of the most advanced medical accelerators in the world. It is the most compact synchrotron, the outer diameter is 5 m and the weight is 15 tons. This kind of accelerator does not use absorbers for proton range correction. That fact makes Protom synchrotron is radiation clean accelerator (radiation is produced only during patient irradiation session). Protom synchrotron is energy efficient facility. The average power consumption of all accelerator complex during treatment is 30 kW. The maximum energy of 330 MeV makes proton tomography of full patient body available [6].

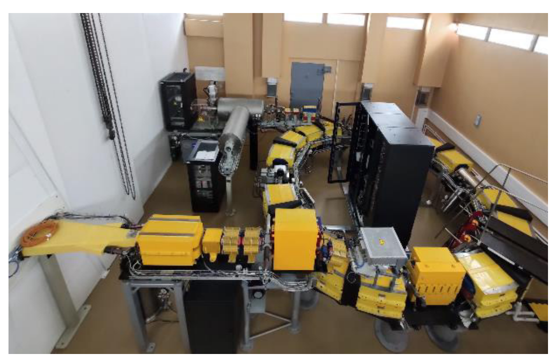

Figure 1: Protom Synchrotron-based Accelerator Complex “Prometheus” in MRRC, Obninisk, Russia.

The first technical run of the prototype of Proton Synchrotron was in 2003. The technical runs of facilities based the synchrotron were performed in 2010 in Protvino City Hospital, Protvino, Russia and Central Military Hospital, Ruzhomberok. In 2011 the technical facility in McLaren Hospital, Flint, MI, USA was successfully performed too. Nowadays proton therapy facilities based on Protom Syn-

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chrotron has been successfully used under clinical conditions more than 5 years. The first patient was irradiated in Protvino City Hospital in 2015. Since 2017 the proton therapy facility works only on biological research [7]. In 2016 treatment process was started in the A. Tsyb Medical Radiological Research Center Obninsk [8,9], Russia, in 2018 in the McLaren Hospital and in 2020 in the Massachusetts General Hospital. The clinical accelerator in MRRC is presented in Fig. 1. Up to date more than 1000 patients were irradiated worldwide most of which have been treated in Russia.

PROTON THERAPY SOLUTIONS OVERVIEW

Protom synchrotron currently is implemented in several proton therapy complexes. Protom synchrotron works as a part of Russian proton therapy complex "Prometheus", US "Radiance 330" complex, and Israel P-Cure facility that is shown in Fig. 2.

Table 1: Proton Therapy Solutions Based on the Protom Synchrotron

Prometheus	**Radiance 330**	**P-Cure Proton Therapy Solution**
Protom Ltd.	Protom International	P-Cure
Russian local granted CE is ongoing	FDA proved CFDA is ongoing	FDA is ongoing Israel is ongoing CFDA is ongoing
Obninsk, Russia Protvino, Russia Ruzhomberok, Slovakia	Flint, MI, USA Boston, MA, USA Middleton, MA, USA	Shilat, Israel

Basic information about these complexes is shown in the Table 1, where there first row is name of the facility, the second one consists of main manufacturers, the third one consists of permissions to treat, and the last one – locations of these facilities. Any synchrotron-based medical facility consists of beam injection system including ion source and linear or tandem accelerator, main accelerator – the synchrotron, beam extraction and transfer channels, medical part including one or several treatment rooms with patient immobilization, positioning and imagine systems.

Figure 2: Protom Synchrotron-based Accelerator Complex in P-Cure, Shilat, Israel.

INJECTORS

Protom Synchrotron uses 3 types of injectors. Two of them are Tandem accelerators produced by Protom ltd. and the last one is RFQ produced by AccSys Technology, Inc. The Table 2 consists of brief comparison of this injectors.

Table 2: Injector Types for Proton Synchrotron

Tandem v.1	**AccSys Technologies RFQ**	**Tandem v.2**
Injection energy 0.9 MeV	Injection energy 1.6 MeV	Injection energy 1.1 MeV
Film recharge (Carbon)	No recharge	Gas recharge (Nitrogen)
"Prometheus" 1st gen	"Radiance 330"	P-Cure PT Solution "Prometheus" 2nd gen

Since 2017 the process of update facilities used Tandem v.1 started. Using Tandem v.2 allows to increase the number of injected and captured protons.

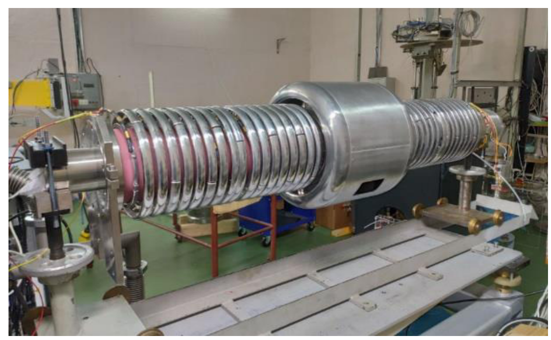

Figure 3: Accelerator tube assembly for Tandem v.2.

The key difference from the previous version was increased injection energy and change of recharge type. Gas recharge made the full system more reliable and allowed to get away from the procedure of changing carbon recharge film. That should be performed at least a few times per year. The Tandem v.2 is shown in Fig. 3.

THE SYNCHROTRON

The synchrotron serves to accelerate the proton beam from the injection energy to the required energy in a given range. The synchrotron provides a high rate of particle acceleration equal to 250 MeV per 0.9 s.

To simplify the design of the accelerator and reduce its dimensions, separate focusing elements are excluded from the magnetic synchrotron system, and edge focusing is introduced into the rotary magnets, which is provided by cuts of magnets from the side of the free gaps. One of the main advantages of this magnetic system is the low power consumption compared to analogues. During the calculation period, measurements of the power consumed by the magnetic system were made. The average value is 30 kW. Main parameters of Protom Synchrotron are shown in Table 3.

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Table 3: Main Parameters of Protom Synchrotron

Range of accelerated proton energies, MeV	30 - 330
Range of energies for treatment, MeV	70 - 250
Acceleration time for 250 MeV, sec	0.9
Intensity of extracted beam, protons per cycle	up to 4×10^9
Outer diameter of the ring, m	5
Accelerator weight, tons	15
Average energy consumption during treatment, kW	30

EXTRACTION CHANNEL

The beam extraction from the synchrotron occurs according to the following scheme: the buildup of betatron oscillations is initiated with subsequent scattering by the internal target.

After that beam enters the electrostatic deflector from the changed orbit, where it is radially thrown from into the Lambertson magnet. In the channel, the focusing lenses and the position correcting magnets are installed. Observation of the beam is carried out from the phosphor-coated screens using the system of visual control. The key parameters of extraction channel variation are presented in Table 4.

Table 4: Parameters of Extraction Nozzles and Scanning System

	Prometheus 1st gen	**P-Cure, Prometheus 2nd gen**
Horizontal field size, mm	700	400
Vertical field size, mm	90	400

Each of Protom synchrotron-based proton therapy facility has active pencil beam scanning system with IMPT mode. Table 5 shows typical beam sizes for several energies.

Table 5: Typical Beam Sizes

Energy [MeV]	**Transverse beam size, σ_x for Gaussian distribution, mm**	**Transverse beam size, σ_y for Gaussian distribution, mm**
70	5,0	5,0
100	3,3	3,3
150	2,6	2,6
250	1,9	1,9

PROTOM MEDICAL SYSTEM

The system includes an armchair designed to fix the patient and move him to the irradiation zone, an x-ray unit represented by a small-dose X-ray tube and a digital X-ray panel (detector).

With their help, the X-ray photographs are taken with a subsequent process of reconstructing them into a three-dimensional image for subsequent irradiation planning. The individual radiograph mode has been put into place in order to verify the patient's position before the start of the treatment [10].

There is a unique Treatment Planning System (TPS) that has been developed by Protom Ltd. It is based on Monte Carlo calculation. The Protom TPS takes into account Multiple Coulomb scattering and proton losses on nuclear interactions. It supports parallel computing technology and is able to use GPU. This TPS is a part of proton therapy complex “Prometheus”. It is used in MRRC as a main TPS.

CONCLUSION

Physical-Technical Center and Protom Ltd. has full range of the technologies for proton therapy that are successfully used under clinical conditions over 5 years. Physical-Technical Center and Protom Ltd. are improving existing solution and developing new ones that are focusing on accuracy of dose delivery and decreasing patient treatment time.

Each of proton therapy facilities based on Protom Synchrotron supports full intensity modulated proton therapy (IMPT) option with high beam delivery accuracy and active pencil beam scanning (PBS) option. Both of these features are native technologies for Protom Synchrotron, there is no need in additional facility updates. Protom Synchrotron was initially designed to support proton radiography and tomography. The last researches have shown that intensity level that is necessary for radiography implementation can be reached with no constructive changes.

According to 5 years of clinical use Proton Synchrotron demonstrated high level of reliability. Downtime for the synchrotron was less than 1%.

All of these parameters together with low cost of the accelerator, low power consumption, fast installation process, absence of radiation in inactive mode let Protom Synchrotron successfully compete other PT commercial solutions. Nowadays more and more hospitals choose proton therapy facilities based on Protom Synchrotron.

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