27th Russian Particle Acc. Conf. RuPAC2021, Alushta, Russia JACoW Publishing
ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-MOPSA40

THE PIPLAN PROTON-CARBON ION RADIATION THERAPY PLANNING SYSTEM

A. A. Pryanichnikov†[1,2], A. S. Simakov[1],
Lebedev Physical Institute RAS, Physical-Technical Center, Protvino, Russian Federation
I. I. Degtyarev, F. N. Novoskoltsev, O. A. Liashenko, E. V. Altukhova, R.Y. Sinyukov
Institute for High Energy Physics named by A.A. Logunov of NRC “Kurchatov Institute”, Protvino, Russian Federation
[1]also at Protom Ltd., Protvino, Russian Federation
[2]also at Lomonosov Moscow State University,
Accelerator Physics and Radiation Medicine Department, Moscow, Russian Federation

Abstract

This paper describes the main features of newest version of the Proton-Carbon Ion Radiation Therapy Planning System (PIPLAN). The PIPLAN 2021 code was assigned for precise Monte Carlo treatment planning for heterogeneous areas, including lung, head and neck location. Two various computer methods are used to modeling the interactions between the proton and carbon ion beam and the patient's anatomy to determine the spatial distribution of the radiation physical and biological dose. The first algorithm is based on the use of the RTS&T 2021 high precision radiation transport code system. The second algorithm is based on the original Ulmer’s method for primary proton beam and adapted Ulmer’s algorithm designed for primary carbon ion beam with energy in the range 100-450 MeV/u.

INTRODUCTION

Today in Russia there are no heavy ion accelerators used in cancer therapy [1]. On the basis of SRC IHEP of NRC “Kurchatov institute” Accelerator Complex U-70 it is planned to create a Ion Beam Therapy Center using the 200-450 MeV/u $^{12}C^{6+}$ ion beams. Currently, a Radiobiological Workbench (RBC) U-70 was created and successfully operated It is shown in Fig. 1.

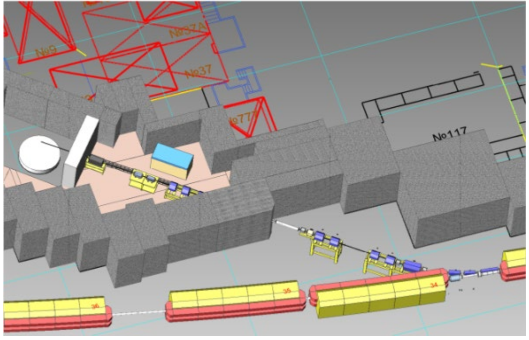

Figure 1: Layout of equipment in the RBC beam transfer line of the U-70 Accelerator Complex.

One of the important areas is the creation of a Radiotherapy Treatment Planning system. The purpose of Radiotherapy Treatment Planning systems is to estimate the dose absorbed by a patient in a radiotherapy session, so that tumors can be irradiated with the strictly necessary dose. Many publications have proved Monte Carlo techniques as a highly accurate dose calculation tool, having the only limitation of computing time cost. Several Monte Carlo based treatment planning systems have been developed and tested at the IHEP U-70 facility for carbon ion therapy. The irradiation of the water phantom has been simulated with the RTS&T and PIPLAN codes.

ION BEAM TREATMENT PLANNING SYSTEM (PIPLAN 2021)

The PIPLAN 2021 Treatment Planning System consist 2 independent methods to Monte Carlo simulation the spatial distribution of the radiation physical and biological dose.

The RTS&T 2021 Precision Simulation Algorithm

The RTS&T [2] code (Radiation Transport Simulation and Isotopes Transmutation Calculation) was assigned for detailed Monte Carlo simulation of many particle types (γ, $e^{\pm}$, p, n, $\pi^{\pm}$, $K^{\pm}$, K_L^0,, antinucleons, muons, ions and etc.) transport in a complex 3D geometry's with composite materials in the energy range from a fraction eV to 20 TeV and calculation of particle fluences, radiation field functionals and isotopes transmutation problem as well. A direct using of evaluated nuclear data libraries (data-driven model) (ENDF/B, JENDL, ROSFOND, BROND, TENDL etc. - total 14 libraries) to N, d, t, ^{3}He,^{4}He particles transport and isotopes transmutation modeling in low and intermediate ($E<200$ MeV) energy regions is the idea of the RTS&T code construction. In general, this approach is limited by the available evaluated data to particle kinetic energies up to 20 MeV, with extensions up to 30 MeV or 200 MeV.

Adapted Ulmer’s Fast Simulation Algorithm

The original Ulmer’s method that is designed for incident proton beam up to 400 MeV [3] was adapted for primary carbon ion beam up to 450 MeV/u. We have developed a model for carbon ion depth dose and lateral distributions based on Monte Carlo highly accurate calculations (RTS&T 2021 code). The model accounts for the transport of primary particles, the creation of recoil pro-

---

† pryanichnikov@protom.ru

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

tons, secondary protons and heavy nuclei as well as lateral scattering of these contributions [4,5].

The RTS&T Geometry Module (New Version Announcement)

The current version of the RTS&T geometry module included in the RTS&T 2021 code contains a "synthetic" (combinatorial-voxel) scheme for describing the geometry of the object with a choice of the boundary localization method (analytical, iterative, or their combination). The capabilities of the geometric module allow to visualize the geometry of complex material structures of an arbitrary degree of complexity and the distribution of calculated functionals in them. The example of volumetric image is shown in Fig. 2. The example of pixel imaging in Fig. 3.

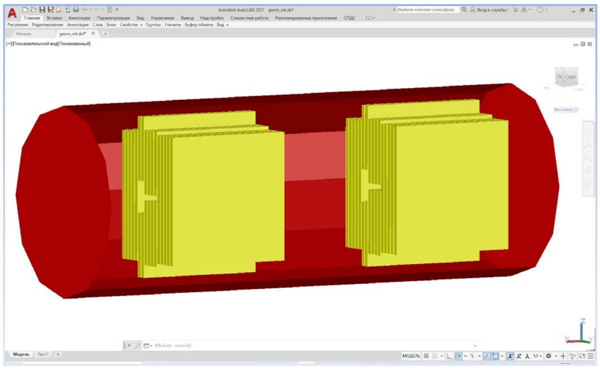

Figure 2: Volumetric image in toning mode of collimator with T-shaped profile.

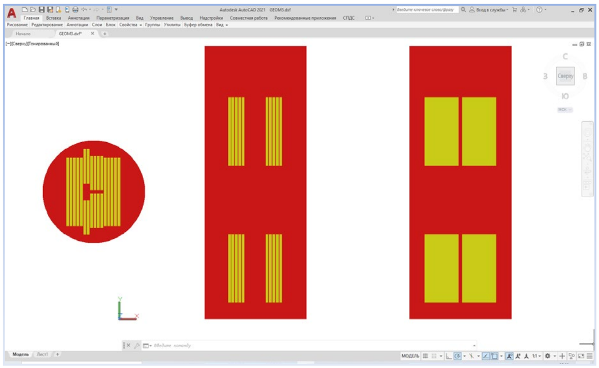

Figure 3: Pixel imaging of a collimator with a T-shaped profile.

BIOLOGICAL MODELING

The RTS&T 2021 code included a versions of the Microdosimetric Kinetic Model (MKM) [6] and Local Effect Model (LEM I-III) with 12 sets of input parameters for various lines of radiosensitive cells, that allows to calculate:

- averaged over the flow (trajectories) and absorbed dose of linear energy transfer (LET);
- relative biological radiation efficiency (RBE) for different levels of cell structure survival (S,%);
- biological dose.

DOSE DISTRIBUTION VERIFICATION

Figures 4-9 represent the results of measurements and Monte Carlo simulations of dose distribution in water phantom for monoenergetic carbon ion sources in the energy range of 200-430.1 MeV/u using the PIPLAN 2021 and RTS&T 2021 codes. In the RTS&T simulation, the CASCADE 1.0 and JQMD 2.0 hadronic generators were used for inelastic hA- and AA-events simulation. The energy losses of incident $^{12}C^{6+}$ ion were calculated using the ATIMA v.1.4.1 [7] code.

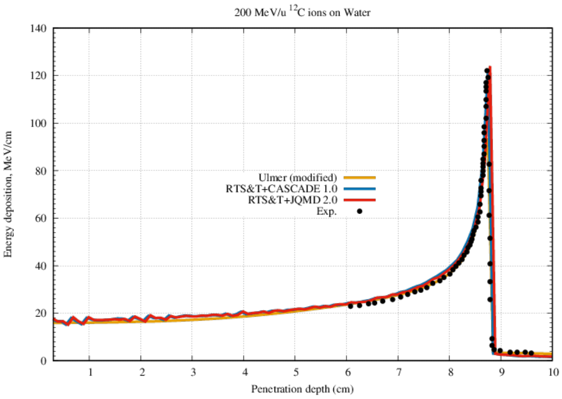

Figure 4: The total absorbed dose versus depth inside water phantom at 200 MeV/u of incident ^{12}C beam (R_{csda}=8.575 g/cm^2).

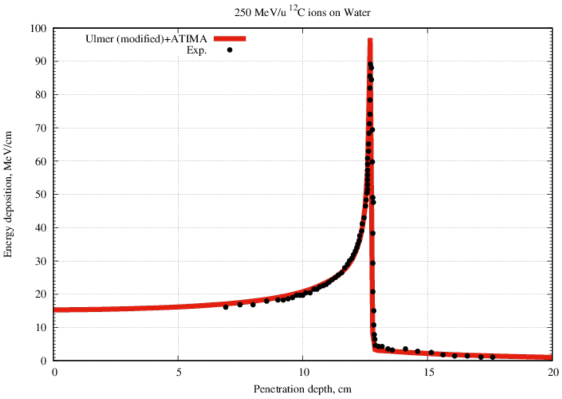

Figure 5: The total absorbed dose versus depth inside water phantom at 250 MeV/u of incident ^{12}C beam (R_{csda}=12.527 g/cm^2).

Figure 4 corresponds to ^{12}C beam energy equal 200 MeV/u, Fig. 5 corresponds 250 MeV/u. Data for carbon ion beam energy of 300 MeV/u is presented in Fig. 6. Depth-dose distribution for 350 MeV/u energy is shown in Fig. 7. The same curve for 400 MeV/u energy is shown in Fig. 8. Maximum energy for experimental data was 430.10 MeV/u, it is presented in Fig. 9. It can be seen from the figures presented above that the results of our calculations are in good agreement with the experimental data.

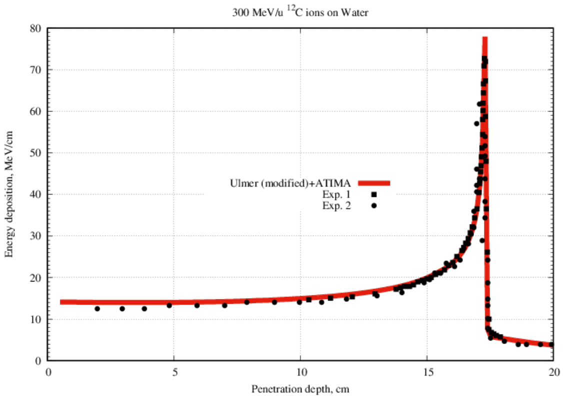

Figure 6: The total absorbed dose versus depth inside water phantom at 300 MeV/u of incident ^{12}C beam (R_{csda}=16.983 g/cm^2).

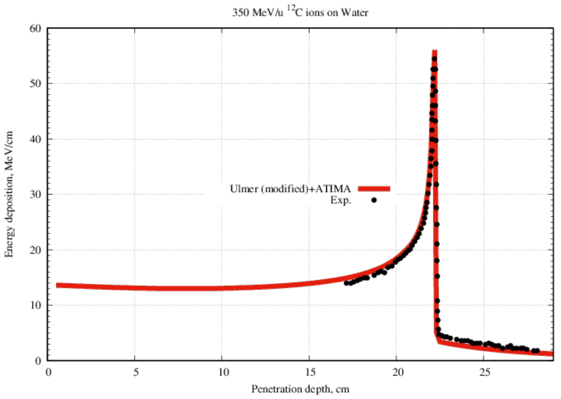

Figure 7: The total absorbed dose versus depth inside water phantom at 350 MeV/u of incident ^{12}C beam (R_{csda}=21.872 g/cm^2).

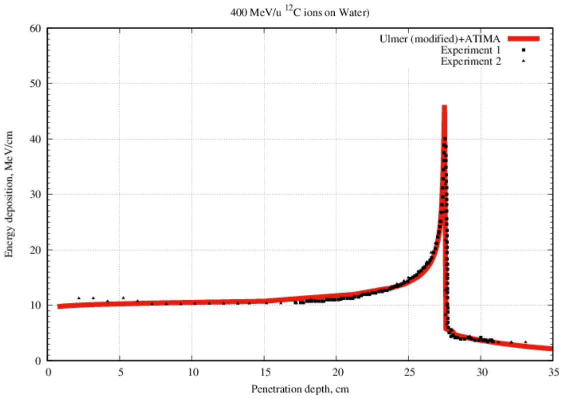

Figure 8: The total absorbed dose versus depth inside water phantom at 400 MeV/u of incident ^{12}C beam (R_{csda}=27.135 g/cm^2).

CONCLUSION

The developed PIPLAN 2021 (Proton-Ion Therapy Treatment Planning System) can be implemented in hardware and software system of Carbon-Ion Therapy Center based on the IHEP Accelerator Complex. Models that are used in PIPLAN can be implemented in already existed Russian proton therapy complexes [8, 9].

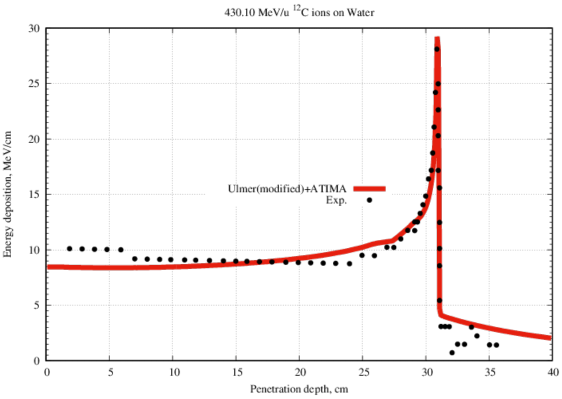

Figure 9: The total absorbed dose versus depth inside water phantom at 430.10 MeV/u of incident ^{12}C beam (R_{csda}=30.463 g/cm^2).

REFERENCES

[1] A. P. Chernyaev *et al.*, “Proton Accelerators for Radiation Therapy”, *Medical Radiology and Radiation Safety*, vol. 64, no. 2, pp. 11–22, 2019. doi:10.12737/article_5ca5a0173e4963.18268254

[2] I.I. Degtyarev *et al.*, “The RTS&T-2014 code status”, *Nuclear Energy and Technology*, vol. 1, no. 3, pp. 222-225, 2015. doi:10.1016/j.nucet.2016.02.006

[3] Varian Medical Systems, “Eclipse Proton Algorithms Reference Guide”, P1026475-001-A, 2019.

[4] L. Sihver, D. Schardt, and T. Kanai, “Depth-Dose Distributions of High-Energy Carbon, Oxygen and Neon Beams in Water”, *Japan. J. Med. Phys.*, vol. 18 no. 1, pp. 1-21, 1998. doi:10.11323/jjmp1992.18.1_1

[5] E. Haettner, H. Iwase, and D. Schardt, “Experimental fragmentation studies with ^{12}C therapy beams”, *Radiation Protection Dosimetry*, vol. 122, no. 1-4, pp. 485–487, 2006. doi:10.1093/rpd/ncl402

[6] A.A. Pryanichnikov *et al.*, “The RTS&T Code Coupled with the Microscopic Kinetic Model for Biological Calculations in Multi-Ion Therapy”, *Phys. Part. Nuclei Lett.*, vol. 17, no. 4, pp. 629–634, 2020. doi:10.1134/S1547477120040378

[7] K. Parodi *et al.*, “Monte Carlo simulations to support start-up and treatment planning of scanned proton and carbon ion therapy at a synchrotron-based facility”. *Phys. Med. Biol.* vol. 57, no. 12, p. 3759, 2012. doi:10.1088/0031-9155/57/12/3759

[8] A. A. Pryanichnikov *et al.*, “Status of the Proton Therapy Complex Prometheus”, in *Proc. 26th Russian Particle Accelerator Conf. (RuPAC’18)*, Protvino, Russia, Oct. 2018, p. 135-138. doi:10.18429/JACoW-RuPAC2018-FRXMH03

[9] A. A. Pryanichnikov *et al.*, “Clinical Use of the Proton Therapy Complex “Prometheus””, *Phys. Part. Nuclei Lett.*, vol. 15, no. 7, pp. 981-985, 2018. doi:10.1134/S1547477118070592

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI