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Salahaddin University-Erbil

Innovative of range verification of Hadron therapy by using FLUCA code

Research Project

Submitted to the department of Physics in partial fulfillment of the requirements for the degree of BSc. in Physics

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بِسْمِ اللَّهِ الرَّحْمنِ الرَّحِيمِ

قَالُواْ سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ

صدق الله العظيم

سورة البقرة الاية32

Supervisor Certificate

This research project has been written under my supervision and has been submitted for the award of the degree of BSc. in (Physics).

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This project is dedicated to:

This thesis is dedicated to: Allah Almighty, my Creator and my Master, My great teacher and messenger, Mohammed (May Allah bless and grant him), who taught us the purpose of life, My homeland Kurdistan, the warmest womb, The University of Salahaddin-Erbil; my second magnificent home; My great parents, who never stop giving of themselves in countless ways, My beloved brothers and sisters; To all my family, the symbol of love and giving, My friends who encourage and support me, All the people in my life who touch my heart.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description
IMRT	Intensity Modulated Radiation Therapy
MC	Monte Carlo
RBE	relative biological effectiveness
HT	Hadron therapy
FWHM	full width at half maximum
LBL	Lawrence Berkeley Laboratory
MCNPX	Monte Carlo N-Particle eXtended

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Cancer is the second major cause of death after cardiac disease around the world, and it is the only major disease for which the death rates are still increasing (NIH, 2012). Currently, the main therapeutic strategies for curing cancer include surgery, radiation therapy, chemotherapy, or any combination of the above. Indeed, the most effective therapy method is surgery, which contributes 22% the overall cure rate. However, for almost 1/3 of patients, the tumor has already spread out before being diagnosed. Radiation therapy, alone or in combination with other treatment modalities, is the second most effective treatment method (VENKATESWARAN,2022).

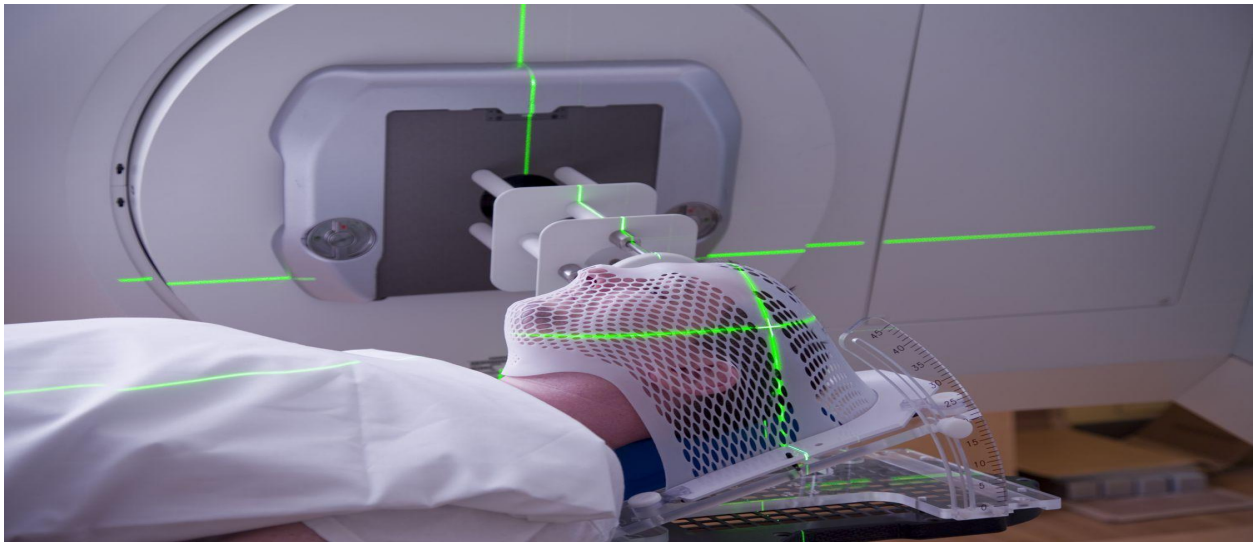

Figure 1.1 Radiation Therapy as Treatment for Cancer (Delaney et al., 2005).

Nowadays, approximately 60% of cancer patients are treated using external beam radiotherapy at some point during cancer management (Delaney et al., 2005), and for the foreseeable future, radiotherapy will have an extremely important role to play in cancer therapy. Energy deposited by radiation can sterilize cells through the production of free radicals in the cell. The higher the delivered dose to the whole tumor, the higher the probability it will be controlled. However, at the same time, normal tissues can also receive radiation or sterilization through similar mechanisms. Thanks to the differences in radiobiological effect between different tissues, normal cells are capable of repairing themselves more rapidly than cancerous cells, Radiotherapy is an important tool for cancer treatment in the past, present, and future (OKAWA, T, 1999). Consequently, fractioned treatment, the

use of repeated applications of relatively low doses of radiation over many days and weeks rather than a one-shot delivery, has been used for many years to enhance the therapeutic ratio between the dose to the normal and tumor tissues. Despite this, the holy grail of radiation therapy is to concentrate radiation dose on the tumor cell whilst simultaneously sparing surrounding healthy tissue as much as possible. In pursuit of this goal, there has been continuous research into improving radiotherapy delivery techniques, since the start of radiotherapy more than 100 years ago. For example, oncologists have been searching for protocols for defining targets and optimizing the prescribed dosage for maximizing outcomes, whilst physicists have been taking use of various kinds of particles and manipulation techniques for improving concentration of dose to the tumor. As such, hundreds of thousands of papers or articles have been published concerning this topic, and there is no doubt that it will continue to be a hot topic in the next decades (MUELLER, 2016).

In particular, during the last 20 years, radiation therapy has made great steps in developing advanced treatment techniques. For example, Intensity Modulated Radiation Therapy (IMRT) utilizes intensity-modulated photon fluencies, instead of homogeneous ones, for conforming doses more precisely to the 3D target shape. Furthermore, different radiation qualities, such as heavier charged particles are being exploited more and more. In particular, protons and carbon ions both have relatively low energy deposited in the entrance path, followed by a pronounced dose maximum in the so-called Bragg Peak region through which superior dose distributions can be obtained, particularly for deep site tumors.

Popularity of Monte Carlo (MC) techniques in the field of medical physics is increasing rapidly in recent years. This is specifically the case for hadron therapy. MC simulations are an essential tool for the design and commissioning of novel clinical facilities, allowing a detailed description of the beam line and the delivery system. Monte Carlo (MC) codes are increasingly spreading in the hadron therapy community due to their detailed description of radiation transport and interaction with matter. The suitability of a MC code for application to hadron therapy demands accurate and reliable physical models for the description of the transport and the interaction of all components of the expected radiation field (ions, hadrons, electrons, positrons and photons). This contribution will address the specific case of the general-purpose particle and interaction code FLUKA. In this work, an application of FLUKA will be presented, i.e. establishing CT (computed tomography)- based calculations of physical and RBE (relative biological effectiveness)- weighted dose distributions in scanned carbon ion beam therapy.

1.2 HADRONTHERAPY

Hadrontherapy (HT) often also denominated ‘particle therapy’ - is a collective word used to indicate the treatment of tumors through external irradiation by means of accelerated hadronic particles. Several kinds of particles have been and are the subject of intensive clinical and radiobiological studies: neutrons, protons, pions, antiprotons, helium, boron, lithium, oxygen ions, and carbon. Among all these possibilities, only two of them –carbon ions and protons – are nowadays used in clinical practice and represent the focus of an ongoing remarkable technological development and science. In this investigation, only carbon ion and proton therapy are discussed. carbon ions and Protons are more advantageous in cancer radiation therapy with respect to X-rays mainly because of three reasons. The release of energy along their path inside the patient’s body is characterized by a large deposit localized in the last few millimeters at the end of their range, in the so-called Bragg peak region, where they produce severe damage to the cells while sparing both traversed and deeper located healthy tissues. Moreover, they penetrate the patient with minimal diffusion and, using their electric charge, a few millimeters full width at half maximum (FWHM) ‘pencil beams’ of variable penetration depth can be precisely guided towards any part of the tumor (SCHARDT,2016).

The third reason pertains to carbon ions - and light ions in general - and is based on radiation biology. Since, for the same range, carbon ions deposit about a factor of 24 more energies in the Bragg peak region with respect to protons, the produced ionization column is so dense to be able to induce direct multiple-strand breaks in the DNA, thus leading to nonrepairable damage. This effect is quantified by an enhancement of the Radio Biological Effectiveness (RBE) and opens the way to the treatment of tumors, which are resistant to X-rays and protons at the doses prescribed by standard medical protocols. In order to treat deep-seated tumors, depths of the order of 25 cm in soft tissues have to be reached. This directly translates into the maximum energies of proton and carbon ion beams which must be 200 MeV and 4 500 MeV (i.e. 375 MeV/u), respectively. (PORCEL ,2014)

1.3 HISTORY OF HADRON THERAPY

Hadron Therapy (HT) is a form of radiation therapy using beams of hadrons to kill cancer cells. The use of hadrons for radiation therapy was first suggested by Robert Wilson in 1946 when Bob Wilson wrote a very illuminating seminal paper1 in which all the basic principles and potentialities of this discipline are stated. I personally find this work very remarkable and still incredibly actual, especially if one considers the fact that precise imaging techniques and enough powerful

accelerators were almost a dream at that time (R. Wilson,1946). At that time, accelerators could not produce heavier charged particle beams to energies sufficient for medical applications. Such energies became possible with the development of the 184-inch cyclotron at the Lawrence Berkeley Laboratory and allowed radio-biological investigation. In 1954, the first patient was treated with proton beams at Lawrence Berkeley Laboratory (LBL), followed by helium ions in 1957, this pioneering work opened the way to the intensive activity performed at the Harvard cyclotron where physicists and radiation oncologists worked together for many decades on three clinical studies: neurosurgery for intracranial lesions (3 687 patients), eye tumors (2 979 patients) and head-neck tumors (2 449 patients). The results obtained by the Harvard group represented the basis for the successive clinical and technical developments of this discipline. It summarizes from the first proposal for HT to the first patients being treated in various countries such as the United States, Japan, and the European Union and the ions used.

A fundamental milestone was accomplished in 1990 when the first patient was treated at the Loma Linda University Medical Center in California, the first hospital-based proton therapy center. This facility featured the first rotating gantries designed for routine treatment. It has to be remarked that, up to this moment, all the HT facilities were based on existing particle accelerators designed for fundamental research, often sharing human resources and beam time with other activities. Moreover, some of these centers made use of low energy – about 70 MeV – cyclotrons, in which only the treatment of ocular pathologies was possible. In the last twenty years, a progressive development of proton therapy took place. From being practiced only in specialized research nuclear and particle physics laboratories, proton therapy is becoming a widely recognized clinical modality in oncology.

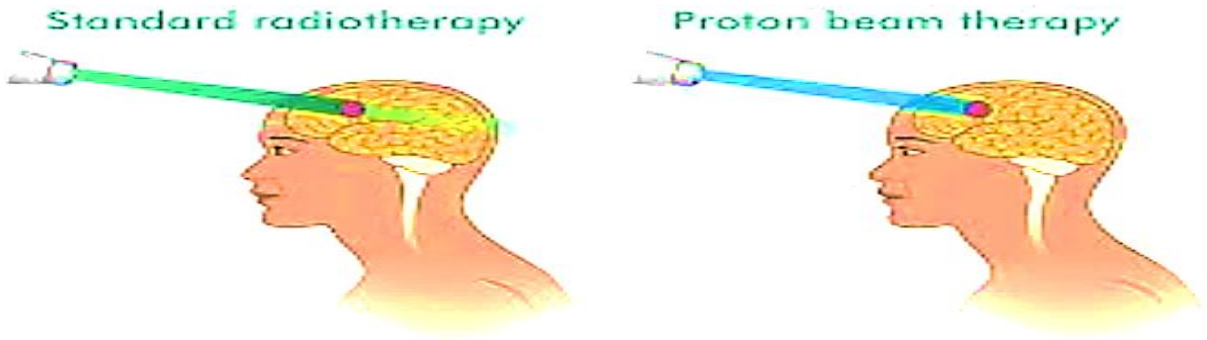

Figure 1.2 Traditional therapy vs hadron therapy. (www.macmillan.org.uk/cancer-information-and-support/treatment)

Monte Carlo simulations play a fundamental role in all those fields in which it is interesting to know the functioning and response of an apparatus or a physical process, with the aim of being able to predict its effects and to be able to modify its characteristics until the desired behavior is obtained. MC simulations are an essential tool for the design and commissioning of novel clinical facilities, allowing a detailed description of the beam line and the delivery system. One of the most useful simulation for hadrontherapy that days use is FLUKA CODE.

1.4 FLUKA CODE ADVANCED FOR RANGE VERIFICATION HADRONTHERAPY

• User friendly graphical Interface (developed in python & C++)

• Minimum requirements on additional software

• Access to FLUKA manual as hyper text

• Checking for release updates of FLUKA and flair

• Import export to various formats: MCNP/X, GDML,…

• Library of materials

• Nuclear wallet cards

• Database of geometrical objects

• Programming python API

• Everything is accessible with keyboard shortcuts

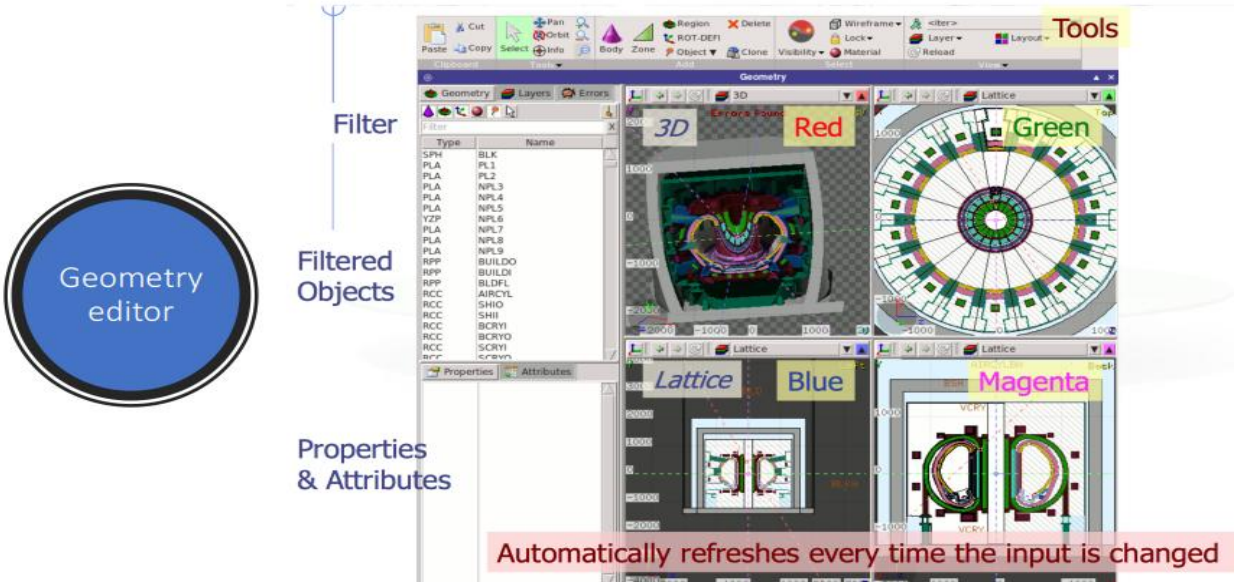

Fig 1.3 Geomerty editor screen of FLUKA CODE.

1.5 FUTURE PERSPECTIVES

For a few years, hadron therapy is facing a deep change that is bringing a relatively small scientific community into a much larger multi-disciplinary contest in which physics, biology, engineering, medicine, law, management, and finance come together and play all important roles. This is mainly due to the large size of this kind of project which, being of the order of 100 million Euro, has a big impact not only on the scientific and technological side but also on the financial, logistic and management aspects. Needless to say that in a complex project, such as the construction of an HT center, many details have to be carefully evaluated and a solid multi-competence project team represents the key to facing all the unavoidable problems and compromises to be assessed from the conception to the running of the facility (PARISI, Gabriele, 2022). In my opinion, two main forces – not always pointing in the same direction - are driving the development of this discipline. On one hand, to be competitive with the continuously increasing performances of conventional radiation therapy, innovative tools and techniques are needed to exploit at best the higher potential of hadron beams. On the other hand, to be able to offer this treatment modality to a larger number of patients, the cost, the size, and the complexity of the equipment have to be reduced. To face these challenges, many scientific and technological developments are ongoing and many new ideas are appearing on the horizon. A non-exhaustive summary of some selected topics is reported here (AMALDI, 2006).

CHAPTER TWO

THEORY

2.1 PHOTON-BASED RADIATION THERAPY VS. HADRON THERAPY

Radiation therapy uses ionizing radiation to kill tumor cells. This biological effect results from a series of physical, physio-chemical, and finally biological mechanisms that are triggered by the energy deposited as the radiation penetrates through the body. The absorbed dose, measured in Gray (Gy) corresponds to the deposition of the amount of energy [Joule (J)], per unit mass of medium [kg]. The equivalent dose, in Sievert (Sv), is equal to the absorbed dose times a weighting factor 1. Ionizing radiation affects both healthy cells and tumors. The relative damage to the tumor tissue compared to the damage in nearby healthy tissue is known as a therapeutic ratio. All improvements in radiation therapy are aimed at improving the therapeutic ratio i.e. achieving high tumor control with a low probability of normal tissue complication. The two main treatment techniques followed are (a) optimization of beam paths through critical anatomical structures, minimizing the dose to healthy tissue. (b) splitting the total required dose (usually 60 Gy) for tumor eradication into multiple smaller dose fractions (2 Gy), delivered over several days or weeks. The second option, fractionation, utilizes differences in cell cycles and damage repair mechanisms between tumor and healthy cells. This may make tumor cells more susceptible to radiation damage. However, in clinical practice, normal tissue complication limits the maximum dose prescribed (HIGGINS, 2017).

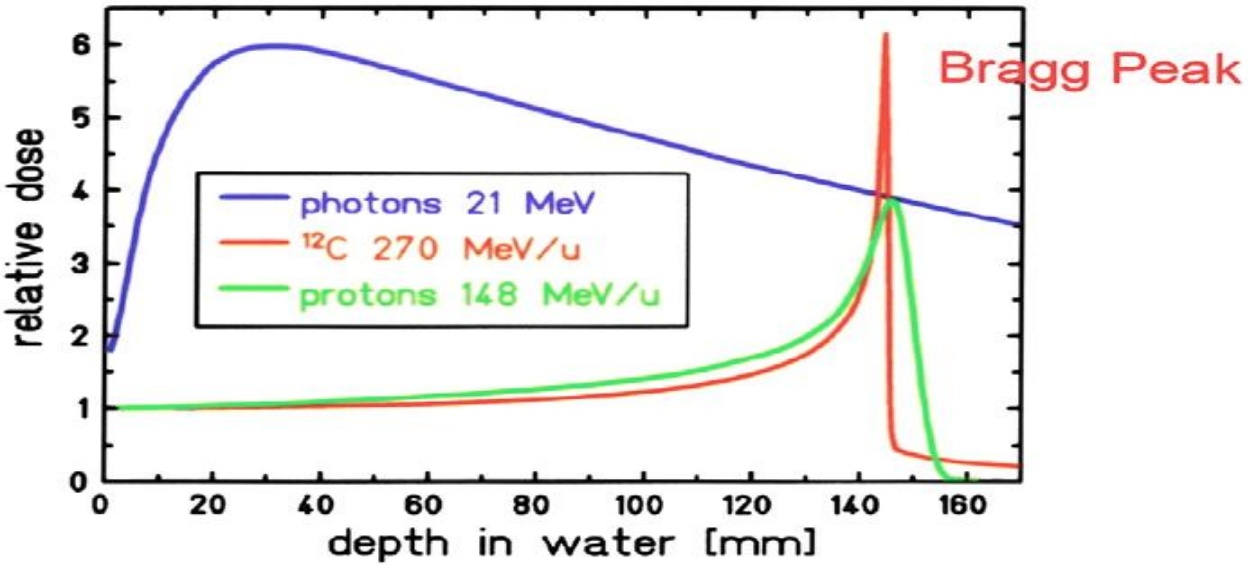

Figure (2.1) Bragg peak of photons, carbon ion, and proton (KIRBY, 2011).

2.2FLUKA CODE

The FLUKA code is a general purpose Monte Carlo code simulating the interaction and transport of hadrons, heavy ions, and electromagnetic particles.

Aspects where MC techniques can be more effective compared to traditional, analytical methods may be summarized as follows

• MC methods take into account more realistically the composition of the human body (1–3), with a possible advantage over the water-equivalent approach typically used in analytical TPS's (Schneider W,2000, Jiang H,2004, and Parodi K,2007)

• MC methods naturally include mixed field description and three-dimensional spread of the particle fluence, reliably describing the transport, and the interaction of the primary beam and of the secondary's (Mairani A,2010, Böhlen TT, 2010).

• In-beam monitoring of the irradiation through positron emission tomography or the detection of prompt photons from nuclear de-excitation can be performed using MC simulations, taking into full account the complexity of the mixed radiation field and tissue stoichiometry (Enghardt W,2004, Sommerer F, 2009, Battistoni G, 2015).

Physics models of superior quality have extended the use of FLUKA to medical applications. Apart from physics, FLUKA is one of the first general-purpose MC codes, which translates DICOM files into voxel geometry as part of the combinatorial geometry package of FLUKA.

For a FLUKA calculation, as for other Monte Carlo codes, a valid input is requested, so a file that should respect the defined features for the FLUKA input CARDs.

Firstly, it is possible, by the editor using the DEFAULT card, to select from a set of default physical settings, recommended for different applications, the correct one depending on the desired quantities.

FLUKA uses for the definition of geometry a Combinational Geometry (CG) package which is defined to work correctly also using charged particles in presence of a magnetic field. Once defined the regions, to each one of them a material has to be associated using the predefined materials stored in the FLUKA's library or creating independently the desired material using the MATERIAL and COMPOUND cards describing the density and the composition of the material. The CG package was well known in the Monte Carlo method but it was originally designed to work with neutral particles, causing problems with the transport of charged particles especially in near-boundaries regions; for this reason, the

algorithm was completely redesigned. Once defined the regions, to each one of them a material has to be associated using the predefined materials stored in the FLUKA's library or creating independently the desired material using the MATERIAL and COMPOUND cards describing the density and the composition of the material. The CG package was well known in the Monte Carlo method but it was originally designed to work with neutral particles, causing problems with the transport of charged particles especially in near-boundaries regions; for this reason, the algorithm was completely redesigned. Differently from other Monte Carlo codes, FLUKA has a variety of built-in scoring options instead of leaving the users to write their ad-hoc scoring routines for each problem. Different typologies of dose could be scored in FLUKA: absorbed dose, effective dose and ambient dose equivalent. The absorbed dose is defined as the ratio between the energy deposited by a particle inside a volume over the mass of the considered volume.

2.3 APPLICATIONS FLUKA CODE IN HADRONTHERAPY

FLUKA simulation has several applications for hadron therapy in various fields like:

• Shielding

• Commissioning of facilities

• Treatment planning and forward checks

• Predictions for monitoring applications (imaging for hadron therapy)

•Design of instruments, dosimetry

• Calculation for shielding and rad. protection in facilities

2.4COMPARING PREDICTIONS DEPTH-DOSE CURVES AND LATERAL DOSE PROFILE

For different high-accuracy data sets, FLUKA is able to reproduce the position of the Bragg peaks of proton and carbon ion beams with a single ionization potential on average within the experimental uncertainties of about 100 μm. The average dose-weighted dose difference ($\frac{\Delta D}{D}$)is below 1% for protons and below 1.5% for carbon ions.

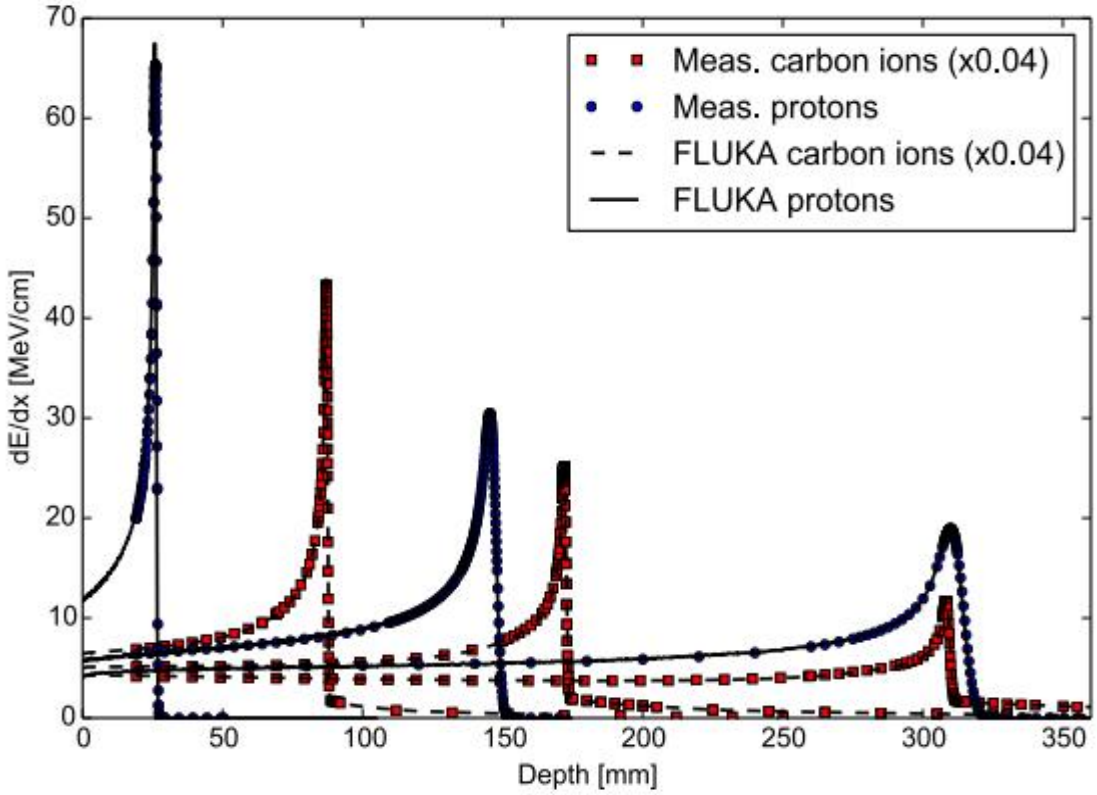

Figure (2.2) FLUKA code comparison with measured data at HIT of depth–dose profiles of protons and carbon ions with therapeutic ranges. The nominal energies before the beamline are 54.19, 142.66, and 221.05 MeV/u for protons, and 200.28, 299.94, and 430.10 MeV/u for carbon ions.

Shows at figure (2.2) exemplary depth–dose profiles simulated by FLUKA for proton and carbon ions in the therapeutic energy range, compared to measurements taken at the Heidelberg ion therapy center (HIT) with the PeakFinder water column (PTW Freiburg). The nominal energies before the beamline for the presented ions are 54.19, 142.66, and 221.05 MeV/u for protons, and 200.28, 299.94, and 430.10 MeV/u for carbon ions. Since nuclear processes determine notably the shape of the depth–dose profiles, especially for carbon ion and high energy proton beams, these comparisons are not only a sensitive benchmark for the electromagnetic physics models but represent, at the same time, an integral benchmark for the nuclear models in their capabilities of predicting non-elastic nuclear interactions.

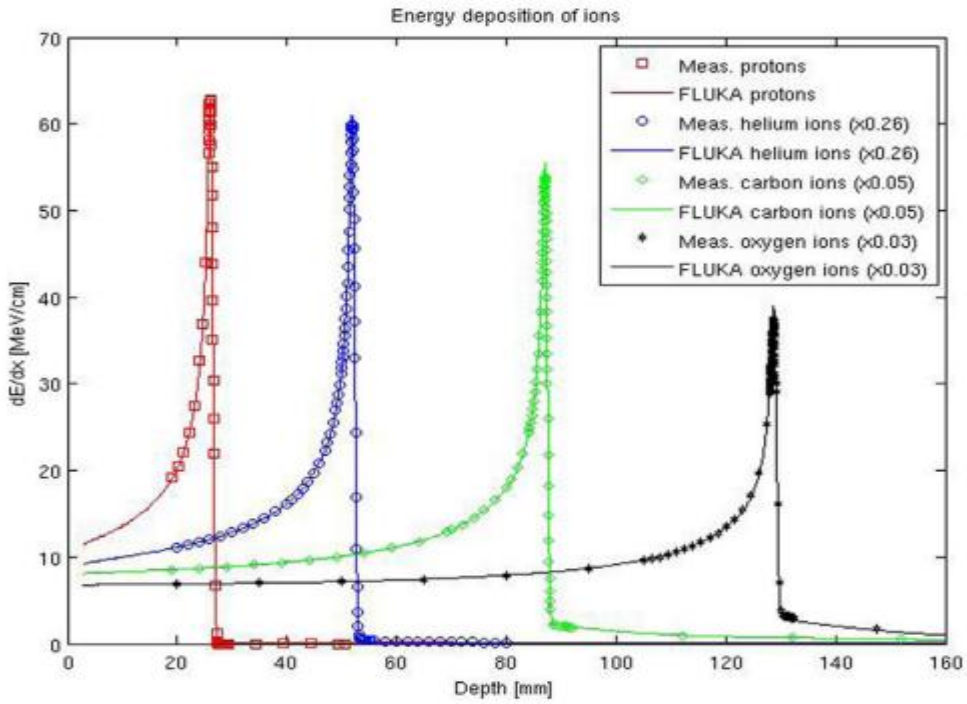

Figure (2.3) FLUKA simulations of depth–dose profiles of protons, helium, carbon, and oxygen ions with therapeutic ranges in comparison with measured data at HIT.

Figure (2.3) shows the comparisons between depth–dose profiles acquired with the above mentioned PeakFinder and FLUKA simulations for the different ions available at HIT and different initial beam energies spanning the whole therapeutic range. The nominal energies before the beamline for the displayed ions are 54.19, 79.78, 200.28, and 300.13 MeV/u, for protons, helium, carbon, and oxygen ions, respectively. Quantitative assessment of the level of agreement between measured and simulated depth–dose distributions of these ions has been determined by calculating the weighted chi-square difference for irradiation of an energy-yielding the same range (ca. 15 cm in water) without ripple filter. The smaller the weighted chi-square difference is, the higher the similarity is between measurements and simulations. The results indicate for the clinically used protons and carbon ions a level of chi-square agreement of 5.8×10^{-5} and 1.1×10^{-4}, respectively.

2.5 DOSE AND BIOLOGICAL DOSE

2.5.1. Charged Particle Interactions in Matter

The most important atomic processes undergone by charged particles when traversing media consist of Coulomb scattering with both atomic electrons and nuclei. The effect of this same basic process is very different for electrons and nuclei because of their difference in mass. Inelastic interactions with atomic electrons are by far the dominant source of charged particle energy losses (also

referred to as electronic stopping power), while they give a contribution proportional to the atomic number Z to angular deflections. Elastic collisions with atomic nuclei result in negligible energy losses – usually referred to as nuclear stopping power – but the angular deflection is proportional to Z2. As a consequence, angular deflections are associated mostly with scattering on atomic nuclei, but for the lightest elements where the two contributions become comparable. Energy losses of charged particles are commonly expressed as an average energy loss per unit path length. The slowing down of energetic protons and ions in the matter is governed by collisions with the atomic electrons and leads to the characteristic shape of the depth–dose profile of heavily charged particles with a peaking energy deposition, the so-called Bragg peak. The nuclear stopping power contribution to the total energy loss of protons and ions in the energy range of relevance for therapy is negligible and will not be discussed further. The implementation of the electromagnetic physics models in FLUKA, which describe continuous energy losses of heavy charged particles, energy loss straggling, delta-ray production, and multiple Coulomb scattering, is briefly described in the following. Electronic Stopping Power Electronic stopping powers are computed by FLUKA starting from the Bethe–Bloch formalism. Several corrections to the standard formulation have been implemented in FLUKA in the recent years, allowing to obtain the high precision requested for the transport of therapeutic beams.

2.6 BIOLOGICAL CALCULATIONS

A major rationale for the application of ion beams in tumor therapy is their increased relative biological effectiveness (RBE) in the Bragg peak region, especially for carbon and heavier ions. For dose prescription in carbon ion therapy, the increased effectiveness has to be taken into account in treatment planning while, in proton therapy, a constant RBE of 1.1 is typically applied as recommended by ICRU (International Commission on Radiation Units and Measurements, 1993). In order to describe the biological effect with FLUKA, an external radiobiological database has to be integrated. The database can be obtained from experimental data or starting from event-by event track structure simulations. This approach was adopted in the past to characterize therapeutic proton beams from a physical and biophysical point of view (Biaggi, M 1999).

The FLUKA recalculations have been performed for a representative cell line characterized by $(\alpha/\beta)ph = 2$ Gy ($\alpha ph = 0.1$ Gy^{-1} and $\beta ph = 0.05$ Gy^{-2}) using the same biological database as implemented in the TPS (Schulte, R. W. 2011). This database is calculated using the radio-biological model LEM I, which has been in vitro and in vivo validated. LEM I is the standard biological model employed at the carbon ion therapy facilities in Europe and has been developed and benchmarked by the GSI biophysics group.

Starting from the electron density and mean ionization energy for the nominal materials corresponding to the segmentation implemented in FLUKA, the carbon ion stopping power relative to water (ρ_s) has been calculated using the approximation proposed in Schneider et al (Schneider U,1996) for proton therapy application, neglecting the shell and density corrections of the Bethe-Bloch formula (which are only minor for the energy range and materials of therapeutic relevance [Ziegler J F, 1999, Sternheimer R M,1982])

$$\rho_S = \rho_e \frac{\log\left[\frac{2m_e c^2 \beta^2}{I_m(1-\beta^2)}\right] - \beta^2}{\log\left[\frac{2m_e c^2 \beta^2}{I_{water}(1-\beta^2)}\right] - \beta^2} \quad (2.1)$$

where ρ_e e is the relative electron density, β_c is the carbon ion velocity, $m_e$is the electron mass and I_m is the mean ionization energy of the target atoms. The carbon ion stopping power relative to water ρ_s represents a good approximation of the WEPL. Hence, in order to match the same experimental WEPL calibration as used in TRiP98 for determining the Bragg peak position in dependence of the HU value, the electromagnetic scaling factors (f_{EM}) for FLUKA have been calculated as:

$$f_{EM} = \frac{WEPL}{\rho_s} \quad (2.2)$$

For validating the introduced approach and the related f_{EM} calculations, we simulated the irradiation of phantoms, corresponding to different CT numbers, with several mono-energetic carbon ion pencil beams. The obtained Bragg peak positions were compared with the TRiP98 results.

2.7 CALCULATION OF ABSORBED DOSE AND RBE-WEIGHTED DOSE

In our simulations, we calculate dose correcting the 'nominal' material density to the 'real' value by means of the same factors used to rescale nuclear processes (Parodi, K., 2007) and for RBE-weighted dose simulations (Mairani, A.,2010). The RBE database consists of α_D and β_D, i.e. the coefficients of the linear and quadratic terms of cell survival after ion irradiation, for the components of the mixed radiation field as a function of the particle energy, particle type and cell line. In the simulation, whenever energy is deposited by a certain radiation type, the following two quantities, in addition to the dose D, are stored $\alpha_D . D$ and $\sqrt{\beta_D} . D$.Then applying the methods described in (Krämer, M.,2006) one can derive RBE-weighted dose results. Dose and RBE-weighted dose results of

TRiP98 are saved with the same spatial resolution of the CT image of the treated patient; the FLUKA grid for scoring dose/RBE-weighted dose has been thus chosen according to the planning CT.

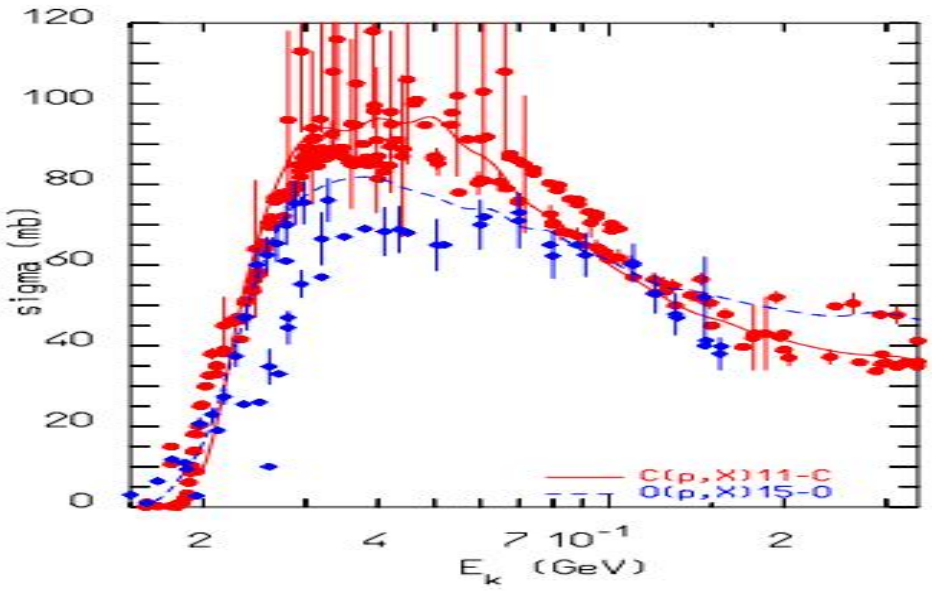

Figure (2.4) FLUKA predictions for the reactions nat,^{12}C(p,x) ^{11}C and nat,^{16}O(p,x) ^{15}O cross sections as a function of projectile energy, compared against data retrieved from the EXFOR library (IAEA. Exfor Library. (2014). Available from: https://www-nds.iaea.org/exfor/exfor.htm).

However, at energies below a few tens of MeV, where binding energies play a crucial role, coalescence is increasingly ineffective in reproducing the data. Recently, a direct deuteron formation mechanism, where the deuteron is formed before being emitted, has been implemented in FLUKA. This mechanism greatly improved the predictive power for reactions, such as (p,d). An example outlining the effectiveness of the new approach and directly relevant for proton therapy monitoring with PET is given in Figure (2.4). The most important reactions for proton therapy are ^{16}O(p,x)^{15}O and ^{12}C(p,x)^{11}C. They can proceed through emission of either independent nucleons or deuterons. The emission of composite ejectiles, like d, t, ^{3}He, and α, is described in FLUKA by the coalescence algorithm in the first stages of the reaction, and by the evaporation of fragments in the equilibrium stages.

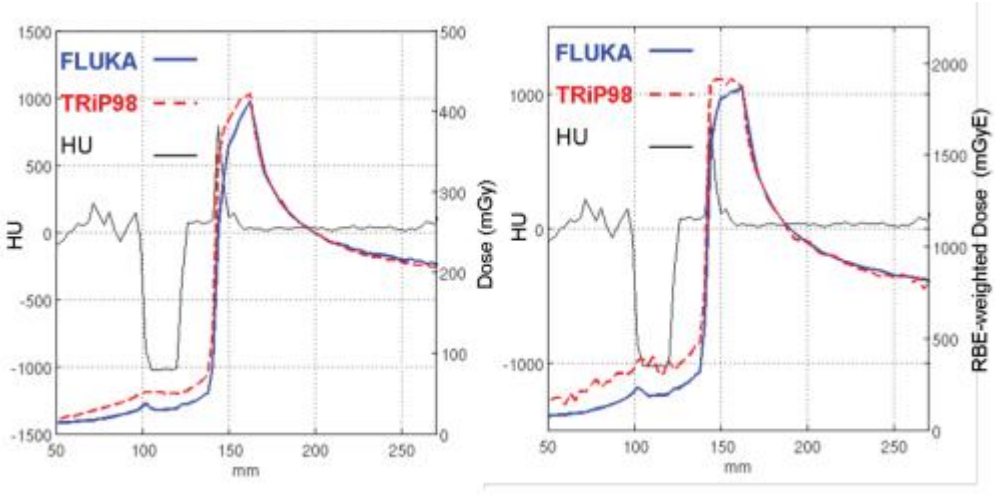

Figure (2.5) Comparison between MC (thick solid line) and TRiP98 (thick dashed line) calculated absorbed depth-dose (left panel) and RBE-weighted dose (right panel).

In Figure (2.5) we presented dose of the RBE dose calculations for a treatment field delivered to a clivus chordoma patient at GSI. In general, the shapes of the MC calculated distributions agree with the TRiP98 ones. Exceptions occur in the cases more sensitive to the limitations of the analytical dose calculations similarly to the findings in proton therapy simulations.

Chapter three

3.1 CONCLUSION

This investigates studies of particle physics and has always offered medicine and biology tools and techniques to study, detect and cure cancer. Hadron therapy represents today one of the major contributions of particle physics to the medical field and is now facing a very exciting phase at the forefront of science and technology.

For most tumors, carbon ion therapy results in improved local control and decreased toxicity in comparison to photons or protons. In some intermediate- and high-risk cancers, the clinical data suggest a survival advantage for carbon ions. Since its beginnings, particle physics has always offered medicine and biology tools and techniques to study, detect and cure cancer. Hadrontherapy represents today one of the major contributions of particle physics to the medical field and is now facing a very exciting phase at the forefront of science and technology.

The electromagnetic and nuclear models of FLUKA enable to reasonably well reproduce measured depth- and lateral-dose profiles in water for all the spectrum of ions of therapeutic interest, making it the code of choice for a generation of TPS input data, as well as a valuable tool to support analytical TPS developments of some commercial vendors. In the last years, special efforts have been devoted to improvements of the FLUKA nuclear interaction models, which provide benchmarked and reliable results for interaction cross sections and particle production by proton, ion beams at therapeutic energies. In particular, they allow to treat in a consistent way the transport and interaction of primary particles and all produced fragments, including transport of electromagnetic particles. All reaction generators share the same equilibrium particle emission, thus profiting together of the past and latest developments of the evaporation, fragmentation, and DE excitation models. Low energy nuclear models are of utmost importance for applications to in vivo verification techniques. FLUKA is presently able to reproduce within experimental errors the production of $\beta+$ emitters by protons at energies of interest for therapy, and at 25% or better accuracy in the case of carbon projectiles. They provide flexible and robust tools to address daily demands required for high quality patient treatment.

Among the manifold applications of the FLUKA MC code for hadron therapy, in this work we have presented a first contribution towards the goal of making a MC validation tool of analytical carbon ion beam treatment planning. In particular, it has been described a methodology for establishing CT-based calculations of absorbed/RBE-weighted dose.

3.2 FUTURE WORK

In the future, for the development of FLUKA, the full source code will be accessible, under a suitable licensing scheme that is under study. The FLUKA web page is also providing access to the present version of the manual, which is still in evolution towards an html format, together with the possibility of having it as a pdf file. Furthermore, the web page is now used to provide a number of documented examples (evolving in time) which help the users to understand the practical utilization of FLUKA, paying attention to the user requests received so far. A series of FLUKA instruction courses are under study, with the possibility of providing, again through the web server, video recordings of the main lectures for more researchers in all around the world could be used for save more time.

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