LASER –DRIVEN HADRON THERAPY PROJECT

F. Scarlat, Valahia University of Targoviste, Targoviste, Romania
F. Scarlat, A. Scarisoreanu, National Institute for Laser, Plasma and Radiation Physics-INFLPR, Bucharest-Magurele, Romania
N. Verga, University of Medicine and Pharmacy, Carol Davila, Bucharest, Romania
Fl. Scarlat, Bit Solutions, Bucharest, Romania

Abstract

The laser beam (10 PW, 15 fs, 150 J, 10^{23} W/cm^2) generated by APOLLON Laser System, now under construction on Magurele Platform near Bucharest may also be applied in radiotherapy. Starting from this potential application, location of malign tumors in patient may be situated, e.g., superficial (≤5 cm), semi-deep (5-10 cm) and profound (>10-40 cm). This paper presents the main physical parameters of a research project for a therapy based on hadrons controlled by laser, for the treatment of superficial and semi-deep tumors. Energies required for pin-pointing the depth of such tumors are 50-117 MeV for protons and 100–216 MeV/u for carbon ions. Hadron beams with such energies can be generated by the mechanism Radiation Pressure Acceleration (RPA). Besides, the control systems to provide the daily absorbed dose from the direct and indirect ionizing radiation at the level of the malign tumor of 2 Gy in 1 or 2 minutes with expanded uncertainty of 3 % are presented.

INTRODUCTION

APOLLON Laser System of 10 PW (150 J, 10^{23} W/cm^2, 15 fs) [1], which is under construction on Magurele Platform close to Bucharest, could employ the relativistic laser beams ($I_0\lambda_0^2>10^{18}$ Wcm$^{-2}\mu$m^2) as an optional application for researches and experiments to accomplish a final project of laser-driven hadron therapy. According to IAEA-TRS 398 standards, the hadrons must have the kinetic energies of 50 to 250 MeV for protons (P) and 100 to 450 MeV for carbon ions (C) [2].

The hadron beams have the in-depth absorbed dose distributions characterized by small relative doses in the entrance area up to the proximity of the practical path end when the dose is rapidly increasing along a very narrow area in the form of a peak called Bragg Peak (Fig. 1). Function of the hadron energy, this peak is occurring at any depth starting from 2.7 cm (50 MeV-P, 100 MeV-C) up to the depth of 38 cm (250 MeV-P, 450 MeV-C), which corresponds to the 1st stage tumors.

In case of tumors of other stages (2nd-4th) the extension of Bragg–Spread Out Bragg Peak (SOBP) is used, with the residual path centred (focused) in the middle of the tumor. At present, the hadron radiotherapy (RT) employs: conventional accelerators of radiofrequency (RF) of NC type, isochronous cyclotron (IBA Protons P: 235 MeV; RF 106 MHz; SC isochronous cyclotron (Varian P; 150 MeV, 72.8 MHz), SC Syncyclotron (Mevion P: 250, 20t), and Synchrotron: slow-cycling (Siemens C:85-430 MeV/u) and proton linacs [3].

At present there are R&D dedicated to obtaining a compact unit. In view of that, a FFAG is in process to be finalized, a cyclinac (cyclotron + high frequency linac) and a Dielectric Wall Accelerator [4].

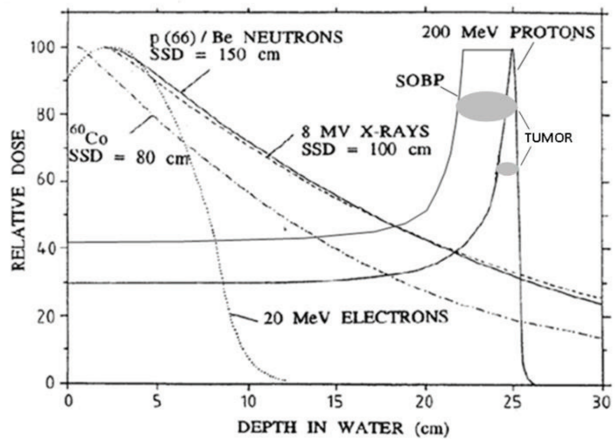

Figure 1: Depth dose distributions in water for X & γ rays, neutron and proton.

Besides, the gradient of the acceleration, limited to 50-100 MV/m in RF linac, may be removed by substituting the RF wave with the laser EM wave that allows an acceleration gradient of 50-100 GV/m [5]. This paper presents the physical parameters of a project employing a laser accelerator for RT of tumors located up to 10 cm in depth using RPA mechanism.

RPA ACCELERATION METHOD

The mechanism called Radiation Pressure Acceleration (RPA) is based on the transfer of energy and the flux of the moment between the linear polarized (LP) laser pulse or circular polarized (CP) laser pulse and the particles inside a solid target. When the target is thin, the acceleration mechanism is called "light sail" (LS) RPA, and when the target is thick (as the case in this paper), the mechanism is called "hole boring" (HB) RPA. The RPA theory is described, for example, in [6].

The HB RPA mechanism developed by Robinson & co. in relativistic regime CP gives the expression for the momentum balance of the plasma surface [7]

$$(2I_0)(1/\gamma_f^2)(1+\beta_f)^2 = 2\gamma_f^2 m_i n_i v_f^2 = (2A/Z)\gamma_f^2 m_p n_{e0} v_f^2 \quad (1)$$

where $I_0=(1/2)\varepsilon_0 c E_o^2$ is the laser radiation intensity ($I_0\lambda_0^2$[W/cm$^{-2}\mu$m^2]$=1.37\cdot10^{18}\cdot\alpha\cdot a_o^2$ cu $\alpha=½$ for LP/CP laser pulse), $\varepsilon_o=8.854\cdot10^{-12}$ [As/Vm] is the permittivity of

ISBN 978-3-95450-148-9

free space, c the speed light, v_f the speed of the laser front or HB velocity, $\beta_f=v_f/c$, $\gamma_f=(1-\beta_f)^{-1/2}$, m_i the ion mass, n_i the ion number density, $A=m_i/m_p$, $m_p=1836m_e$ is the proton mass, m_e the electron mass, Z the ionic charge state and $n_{eo}=n_iZ$ the electron density. Also, E_o [TV/m]=$2.7\cdot10^{-9}I_o^{1/2}$ [W/cm^2]=$3.21a_0/\lambda_0$ [μm] is the peak amplitude of the transverse electric field of LP laser pulse where λ_0 is the wavelength [8]. In the relation of the monochrome radiation I_0 above, the parameter a_0–figure of merit-is the dimensionless amplitude of the transverse electric field E_0 of a LP laser pulse

$$a_0 \equiv eE_0/m_e\omega_0 = 0.85\cdot10^{-9}I_0^{1/2}[W^{1/2}/cm]\lambda_0[\mu m] \qquad (2)$$

and $a_0/\sqrt{2}$ for the CP laser pulse, with e the electric charge and $\omega_0=2\pi c/\lambda_0$ the frequency of laser wave. Since parameter a_o, is the ratio between the EM wave energy and the electron energy at rest, it indicates the laser operation regimes. For the acceleration of the electron ($m_{0,e}$=0.511 MeV/c^2), the operation regime becomes relativistic when $a_0\geq1$. The acceleration of the proton ($m_{0,p}$=938.27 MeV/c^2) at relativistic energies (a_o=1836) requires an intensity $I_o\lambda_0^2=4.62\cdot10^{24}$ [Wcm^{-2}μm^2] [9].

The second important parameter related to the density of a target ($\rho=m_in_i$, $\rho(H^+)=1$ g·cm^{-3}, $\rho(C)=2.27$ g·cm^{-3}), introduced in [6], as a figure of merit Ξ, noted by b_o in this work, is the dimensionless amplitude of the peak intensity

$$b_0 \equiv I_0/\rho c^3 = (Z/A)\left(m_e n_c/2m_p n_{e,0}\right)a_0^2 \qquad (3)$$

where $n_c=m_e\varepsilon_0\omega_p^2/e^2=2I_0/\alpha\cdot m_ec^3a_0^2$ is the critical density defined as the electron density at which the plasma frequency $\omega_p=5.64\cdot10^4$ (n_c[cm^{-3}])$^{1/2}$ becomes equal with the laser frequency $\omega_0=2\pi c/\lambda_0$. The overdense plasma acts like mirror when $\lambda>\lambda_0$ or ($n_e<n_c$, $\omega_0<\omega_p$). The parameter b_0 determines the value of the laser intensity I_0, required to obtain the kinetic energy (P:250 MeV and C:450 MeV/u) and intensity of the hadron beams (10^{10}pps) for therapy. Experimental the laser pulse intensity is measurable by determining the laser pulse energy $\mathcal{E}_0$, the pulse duration τ_{FWHM} at full-width at half maximum and the spot radius. Also, it is possible to determine the peak power P_p, the peak electric field E_p, HB velocity β_f, the accelerated ion kinetic energy T_i, the conversion efficiency of laser energy to the ion energy χ, and the total number of ions per bunch that can be accelerated N_i.

PROJECT PHYSICAL PARAMETERS

Employing the HB-RPA mechanism it was possible to determine the system parameters of the laser-driven hadron therapy research project at lab level.

After having commissioned the APPOLON 10 PW laser system, the experiments with the beams generated by the laser are started. The preliminary main parameters are presented in Tables 1 & 2 [9].

Table 1. Main Parameters for the Proton Therapy

Quantity	Simbol [UM]	Minim value/ Maxim value
1. Proton beam		
Kinetic energy	Tp [MeV]	50/116.70
Magnetic rigidity	BR[Tm]	1.02/1.61
2. Laser beam		
Amplitude parameter	a_0	347/575
Electric field	E_0 [PV/m]	0.866/1.434
Laser intensity	I_0 [W/cm^2]	$1\cdot10^{23}/2.75\cdot10^{23}$
Pulse width	τ [fs]	144/158
Peak power	P_0 [PW]	7.1/8.4
Beam area	A [μm^2]	7.1/3.14
Pulse energy	$\mathcal{E}$ [kJ]	1.02/1.36
3. Proton target		
Intensity parameter	b_0	0.03688/0.10193
Electric field	E_{x0} [PV/m]	0.737/1.22
Conversion efficiency	%	27.75/16.93
Acceleration time	τ_{acc} [fs]	1.4/1.32
Target thickness	d [μm]	6.98/11.50

Table 2. Main Parameters for the Carbon Ion Therapy

Quantity	Simbol [UM]	Minim value/ Maxim value
1. Carbon ion beam		
Kinetic energy/nucleon	$T_{u,I}$ [MeV]	100/215.83
Magnetic rigidity/nucleon	BR[Tm]	1.476/2.235
2. Laser beam		
Amplitude parameter	a_0	347/572
Electric field	E_0 [PV/m]	1.964/3.254
Laser intensity	I_0 [W/cm^2]	$5.17\cdot10^{23}/1.42\cdot10^{24}$
Pulse width	τ [fs]	207/221
Peak power	P_0 [PW]	16.23/44.6
Beam area	A [μm^2]	3.14/3.14
Pulse energy	$\mathcal{E}$ [kJ]	3.4/9.8
Ion numbers	N_i	$6.86\cdot10^{12}/1.16\cdot10^{13}$
3. Carbon ion target		
Intensity parameter	b_0	0.08428/0.23097

ISBN 978-3-95450-148-9

Electric field	$E_{x,0}$ [PV/m]	1.57/2.35
Conversion efficiency	%	36.73/49
Acceleration time	τ_{acc} [fs]	11.32/7.54
Target thickness	d [µm]	13.90/21.38

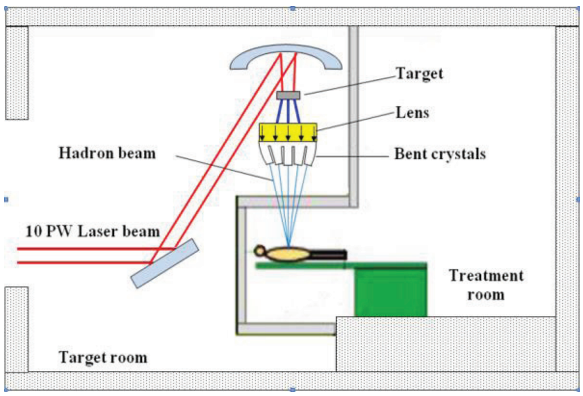

Figure 2: Proposal of an optical-laser gantry system which using mirrors and the phenomem of chaneling in bent crystals as steering, bending and focusing device for hadron beams.

The reference point for this project is represented by work [10] which is a synthesis of 2 versions on the use of laser accelerators. With the first version, a conventional accelerator is substituted with a laser accelerator and the target is located at the target chamber entrance. With the second version (Fig. 2) the laser beam is guided by mirrors up to the target located in the Gantry system, above the treatment table. We consider that the second version, the one which is to use the channelling phenomenon in bent crystals for to make the hadron beam bending and focusing towards the tumor, is the best.

As an example, see the channelling properties for P (50-250 MeV) and C (100 MeV/u-450 MeV/u) in the case of employing crystals of type silicon /germanium /tungsten, Tsiganov radius is of 16.3/7.8/2.1 [cm] respectively the equivalent magnetic fields are of 6-15/13-34/48-115 [Vs/m^2] for protons and 105-250/227-523/885-1942 [Vs/m^2] for carbon ions [11].

In case of this project, the first version is not considered because of the unavailability of a gantry system to be adjusted (modified). The second version cannot be applied either because it take much time to get the research results of the channelling phenomenon in bent crystals. Therefore we decided on a third version presented in Fig. 3 [12].

This version offers the same device for making, bending and focusing the hadron beams (P & C). The physical parameters of the hadron beams will serve to elaborate the opto-electronic design.

This assembly will be a transportable module that is to be component – by – component inserted and then assembled, or it may be placed as a unit in the target chamber of the 10 PW laser. It will be used to finalize the structure, geometry and characterization of the target. The hadron RT successful application depends on.

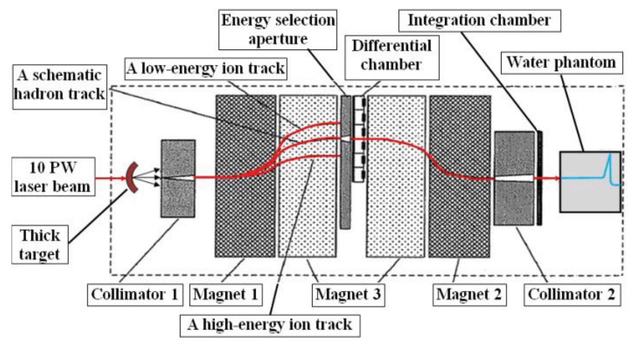

Figure 3: A schematic diagram showing the hadron generation and beam formation in fixed geometry [12].

BEAM MONITORING

Absorbed Dose

The absorbed dose to water when irradiated by hadron beams of quality Q (= Q_P or Q_C) is given by relation [2]

$$D_{w,Q} = M_Q N_{D,w,Qo} k_{Q,Qo} \ , \qquad (4)$$

where M_{corr} is ionization chamber reading in [C] corrected for influence quantities, $N_{D,w,Qo}$ [Gy/C] the absorbed dose to water calibration factor of ionization chamber in a beam of quality Qo(=^{60}Co), and $k_{Q,Qo}$ the beam quality correction factor to account for the use of the calibration factor in a different beam quality Q.

$$k_{Q,Qo} = \frac{(s_{w,air})_Q (W_{air}/e)_Q p_Q}{(s_{w,air})_{Qo} (W_{air}/e)_{Qo} p_{Qo}}. \qquad (5)$$

In our case, $k_{Q,Qo}$ for proton or carbon ion beams, is given by the relation (5) where $s_{w,air}$ is the water to air mass collision stopping power ratio, (W_{air}/e) is the mean energy required to produce an ion pair in dry air and p is a correction factor accounting the perturbation by the presence of the ion chamber in the phantom.

The factors specific to hadron beams Q (Qp&Qc) have the following values: $(s_{w,air})_{Qp}/(w_{air}/e)_{Qp}/p_{Qp}$=function of energy/34.50/1.0 and for $(s_{w,air})_{Qc}/(w_{air}/e)_{Qc}/p_{Qc}$=1.330/34.23/1.0. The values in case of the calibration at the ^{60}Co γ radiation beam quality (Q_0=Q_{Co}) for a PTW 31010 Markus type plan parallel ionization chamber are $(s_{w,air})_{Qo}/(w_{air}/e)_{Qo}/p_{Qo}$=1.133/33.97/1.003 [-/JC^{-1}/-] [13].

Combined Uncertainty

IAEA TRS 398 recommends the use of ionization chambers for depth values of z≥0.5 g/cm^2 for protons and z≥2 g/cm^2 for carbon ions. The uncertainty of the charge M_Q can be assessed by statistical analysis of a series of observations. The uncertainty of M_Q is of type A.

The uncertainties of $N_{D,w}$ and $k_{Q,Qo}$ are of type B. The combined uncertainty, u_C, of absorbed dose $D_{w,Q}$ in the quadratic addition of type A and B uncertainties is [14]:

ISBN 978-3-95450-148-9

$$u_c(D_{w,Q}) = \sqrt{u_A^2(M_Q) + u_B^2(N_{D,w,Qo}) + u_B^2(k_Q)} \quad (6)$$

Assuming no correlation between the components, the expression of the relative combined standard uncertainty yields.

$$\frac{u_c^2(D_{w,Q})}{D_{w,Q}^2} = \left(\frac{1}{M_Q}\right)^2 u^2(M_Q) + \left(\frac{1}{N_{D,w,Qo}}\right)^2 u^2(N_{D,w,Qo}) + \left(\frac{1}{k_{Q,Qo}}\right)^2 u^2(k_{Q,Qo}) \quad (7)$$

Standard uncertainties in D_w(TRS 398, ICRU 78) are $u(N_{D,w})$=0.6 in SSDL for $k_{Q,Qo}$ calculated of 2-2.3 for protons and of 3-3.4 for carbon ions [15].

Aspects of a Control System for Particle Therapy

The therapy employing the ion beams shows some important parameters that need to be subjected to a control. The energy of the laser pulse, $\mathcal{E}_0$, transferred to the ion beam, $\mathcal{E}_i=N_iT_i$ with the energy conversion efficiency χ given by HB-RPA mechanism ($\chi\mathcal{E}_0=\mathcal{E}_i$), successively amplified with the pulse repetition frequency f_R, determines the beam average power P_{rms}, and then amplified by the irradiation time t_S, with the number of irradiation sessions n_S, it determines the total energy absorbed into the tumor, $\mathcal{E}_T=m_TD_T$. Based on the energy balance relation, it is possible to determine the number of ions per bunch $N_i=m_TD_T/n_Sf_Rt_S\mathcal{E}_i$ required to apply the dose D_T(=2/70Gy) in n_S(=1/35) irradiation session. In point of the legal aspects related to the control system of such parameters, they are certified by the National Commission for Nuclear Activities Control (CNCAN, Romania). Also are met the ALARA criteria. [16].

CONCLUSIONS

In this paper, the method employed is based on HB-RPA mechanism aimed to generate hadrons by means of thick targets.

By means of the mechanism was selected the parameters of the laser accelerator supplying hadron beams for therapy of malign tumours located up to 10 cm.

They constitute input main parameters for the opto-electronic project of the gantry system

The gantry system is a device capable to be installed inside the 10 PW laser target chamber. It was selected both for studying target geometry and for selecting the beam energy.

REFERENCES

[1] N.V. Zamfir, "Extreme Light Infrastructure – Nuclear Physics ELI-NP", Experimental Programme Workshop at ELI-NP, Bucharest , Romania, (2012).

[2] IAEA TRS 398, "*Absorbed dose determination in external beam radiotherapy. An international code of practice for dosimetry based on standards of absorbed dose to water*", Tehnical Report no 398.

[3] U. Amaldi et al.,"Accelerators for hadrontherapy: From Lawrence Cyclotrons to Linacs", Nucl. Instr. and Meth.in Phys. Res. A, 620 (2-3), 577 (2010).

[4] K.W.D. Ledingham, P.R. Bolton, N. Shikazono,C - M. Ma, "Towards Laser Driven Hadron Cancer Radiotherapy: Review of Progress", arxiv.org/abs/1405.2657, 12 May 2014.

[5] E. Esarei, P. Sprangle, J. Krall, A. Ting, IEEE Transactions on Plasma Science, 24 (2), 252 (1996).

[6] A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys.85, 751 (2013).

[7] A.P.L. Robinson, P. Gibon, M. Zepf, S. Kar, R.G. Evans and C. Bellei, Plasma Phys. Control. Fusion 51, 024004 (2009).

[8] P. Sprangle, E. Esarey and J. Krall, Bull. Am. Phys. Soc. 40, 1861 (1995).

[9] F. Scarlat, A. Scarisoreanu, N. Verga, Fl. Scarlat, C. Vancea, Journal of Intense pulsed Lasers and Applications in Advances Physics, 4 (4) 55 (2014).

[10] S. V. Bulanov and V. S. Khoroshkov, Plasma Phys. Rep.28, 453, 2002.

[11] R.A. Carrigan Jr., "*On the possible applications of the steering of charged particles by bent single crystals including the possibility of separated charm particle beams*",FERMILAB-Pub_80/45-EXP 7850.

[12] C.-M. Ma, I. Veltchev, E. Fourkal, J.S. Li, W. Luo, J. Fan, T. Lin and A. Pollack, Laser Phys.,16 (4) 1 (2006).

[13] F. Scarlat, N. Verga, A. Scarisoreanu, E. Badita, M. Dumitrascu, E. Stancu, C. Vancea, Fl. Scarlat, Journal of Intense Pulsed Lasers and Applications in Advanced Physics, 3 (2) 15 (2013).

[14] F. Scarlat, A. Scarisoreanu, R. Minea, E. Badita, E. Sima, M. Dumitrascu, E. Stancu, C. Vancea, "Secondary Standard Dosimetry Laboratory at INFLPR", Optoelectronics and Advanced Materials – Rapid Communications, Vol.7, No.7-8, p.618-624, August 2013.

[15] IAEA TEDOC 1585 "*Measurements Uncertanity. A Practical Guide for Secondary Standard Dosimetry Laboratories*", (Vienna 2008).

[16] O. Sotolongo-Grau, D. Rodríguez-Pérez, J. A. Santos-Miranda, O. Sotolongo-Costa, J. C. Antoranz, Math. Med. Biol., 26 (4) 297 (2009).

ISBN 978-3-95450-148-9