DESIGN OF A FAST-CYCLING HIGH-GRADIENT ROTATING LINAC FOR PROTONTHERAPY

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Abstract

General interest has been shown over the last years for the development of single room facilities serving a population of about 2 million people for proton cancer therapy. Compact machines are needed to accelerate proton beams of few nA up to 230 MeV. In this framework the project TULIP (TUrning LInac for Protontherapy), patented by TERA Foundation, foresees a linac mounted on a rotating gantry used as a booster for protons previously accelerated by a cyclotron. The linac is composed of modular units powered by independently controlled klystrons. The RF power transmission is made possible by high power rotating joints developed in collaboration with CLIC group. The final beam energy can be varied in steps of few MeV from pulse to pulse by amplitude and/or phase modulation of the klystron signals, making possible the implementation of active spot scanning technique with tumor multipainting. The present paper provides the main characteristics of TULIP, describing the different choices for the linac design parameters together with the structural design of the supporting gantry and of the final beam line.

INTRODUCTION

Protontherapy is an advanced radiotherapy technique which makes use of fast proton beams for the treatment of deep seated tumors. The typical energy for treatments is up to 230 MeV, which corresponds to a penetration of about 32 cm in water equivalent tissues. An average beam current of few nA is enough to obtain a dose rate of 2 Gy/min in a 1 liter target. The design of novel compact accelerators allowed in the last years the development and the construction of single room facilities. In this framework the TERA Foundation is developing a single room facility design based on the cyclinac concept [1] called TULIP (TUrning LInac for Protontherapy). TULIP is a high-gradient standing wave Side Coupled Linac (SCL) working at 3 GHz which boosts the energies of the protons coming from a commercial cyclotron from 24 MeV up to 230 MeV. It is mounted on a mechanical structure which can rotate of 220 degrees around the patient couch. An artistic view of the TULIP design is shown in Fig. 1.
As shown in the picture, the linac is powered by eleven commercially available klystron modulator systems of 10 MW peak power which can deliver 4 μs pulses at a repetition rate up to 200 Hz. This particular configuration of the linac, divided into eleven independents RF units, allows a *fast* and *active* beam energy modulation, obtained by acting on the voltage and phase of the klystron signals. The high repetition rate and the possibility of modulating the beam current with a computer controlled pulsed external source, allows the combined use of a feedback system in three dimensions and the multi-painting technique (for at least 10 times) to compensate for organ movements.

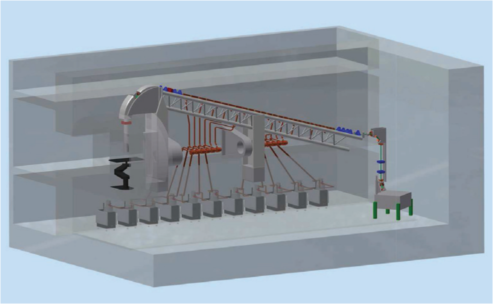

Figure 1: Artistic view of TULIP. The 24 MeV cyclotron TR24 by Advanced Cyclotron Systems (ACS) is used as pulsed injector.

RF DESIGN AND LINAC LAYOUT

The linac design has been performed with the code DESIGN [3], based on the electromagnetic parameters of the cells obtained with POISSON SUPERFISH simulations. The cell geometry has been optimized to maximize the shunt impedance ZT^2 and minimize the ratio between maximum surface electric field and average axial gradient E_{max}/E_0. The influence of different geometrical parameters on the above mentioned parameters has been studied at different energies corresponding at values of β ranging from 0.22 to 0.59. An example of the accelerating cell geometries is shown in Fig. 2 and the most important parameters are collected in Table 1. The linac layout has been carefully studied in order to meet several requirements: (i) the linac has to be short enough to keep the total length of the facility below 25 meters and the total height of the gantry below 5 meters; (ii) it should be possible to modulate the energy of the output beam in the range from 70 to 230 MeV while the energy spread of the beam should stay below 0.5%, allowing for a sharp distal fall-off of the dose into the tumoral tissues [4],[5]; (iii) the machine should be able to deliver about $5 \cdot 10^7$ protons per pulse with an average repetition rate of 120 Hz.

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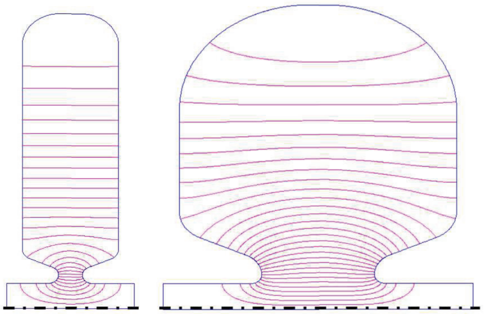

Figure 2: Initial and final accelerating cell geometries of TULIP.

Table 1: Range of the most important geometrical and electromagnetic parameters of the linac

Quantity [unit]	**Initial**	**Final**
Bore hole diam. [mm]	6.0	6.0
Cell diameter [mm]	70.0	70.0
Cell length [mm]	11.4	29.5
Q value	5100	11200
Z [MΩ/m]	37	107
E_{max}/E_0	7.0	4.5
$S_{c,max}/E_0^2$[MV/m]	0.88	0.55

Linac Layout

The linac is composed of tanks, which are made of a certain number of identical cells. The length of each tank is graded in order to keep the synchronism with the beam. Between one tank and the next one a space ranging from 7.8 to 13.3 cm is left for positioning the Permanent Magnetic Quadrupoles (PMQs) which create a quasi periodic FODO channel. The tanks belonging to the same RF unit are coupled together through the bridge coupler which is also used for injecting the power coming from the klystrons. The 11.3 meters long linac is made of a first low gradient section composed of 12 tanks divided into three RF units, which accelerate the protons up to 69 MeV in 3.4 meters. The average effective accelerating gradient in the first section is about 21 MV/m. The second section of the linac is divided into 8 units, with two tanks per unit, and allows to accelerate the beam up to the required 230 MeV in less than 8 meters. In this part the average gradient is around 29 MV/m. This subdivision of the linac is necessary to achieve the desired beam energy modulation (as explained in the section dedicated to the beam dynamics studies), and it also allows to keep the maximum surface electric fields E_{max} below 170 MV/m with a maximum modified Poynting vector $S_{c,max}$ of 0.6 MW/mm^2. In agreement with what has been obtained by CLIC at 12 GHz and 30 GHz, the results of high gradient tests, conducted by TERA in collaboration with the CLIC RF Group, showed that gradients as large as 35 MV/m can be reliably obtained at 3 GHz, with BDR (Breakdown Rate) of less than $3 \cdot 10^{-6}$ bpp/m [2]. This would correspond to miss one spot every two treatment sessions, which typically last 2-3 minutes. The main parameters of the linac are summarized in Table 2.

Table 2: Main characteristics of the linac

Quantity [unit]	**Section 1**	**Section 2**
Output energy [MeV]	70	230
Number of units	3	8
Tanks per unit	4	2
Total length [m]	3.4	7.9
ZT^2 [MΩ/m]	43	76
Avg. E_0 [MV/m]	22.8	29.4
Max. surf. field [MV/m]	140-150	170-125
Peak power [MW]	22	58

RF Rotary Joints

The total RF peak power is 110 MW, which - with a typical RF pulse length of 3.5 μs and a repetition rate of 120 Hz - requires about 150 kW of plug power. The RF power, produced by the klystron located in the adjacent klystron gallery, has to be transmitted to the rotating structure which supports the linac. This is obtained through novel RF rotary joints (proposed by I. Syratchev, CERN) which consist of double choked mode converters from rectangular TE_{10} mode to circular TM_{01}. In order to test the high power behavior a prototype has been designed and is now under construction at CERN.

BEAM DYNAMICS STUDIES

The beam dynamics of the linac has been studied with the multi-particle tracking code LINAC [3]. The input beam is simulated as a 4D water-bag distribution with an energy spread of 1%. Simulations have been performed for different values of input beam emittance. The transmission in the longitudinal plane is around 12% due to the fact that linac buckets are much smaller than the bunches coming from the cyclotron which has an RF frequency of 85 MHz. The geometrical transverse acceptance of the linac has been calculated and reaches 8 π mm mrad (Fig. 3).

For an input beam with a geometrical emittance (1 rms) of 10 π mm mrad in the horizontal and vertical planes, the combined transverse and longitudinal transmission is evaluated to be around 6%, due to cross-talking between the transverse and longitudinal planes. By using this figure, currents of the order of 30 μA, during 5 μs pulses at a repetition rate of 120 Hz, are needed from the cyclotron to obtain 1 nA of average current at the output of the linac. Typically, currents of 300 μA are extracted from the TR24 cyclotron [6]. Contacts with ACS have been taken to further investigate the properties of the extracted beam.

Beam Energy Modulation

The beam energy modulation is simulated by progressively reducing the field amplitude in the last active unit.

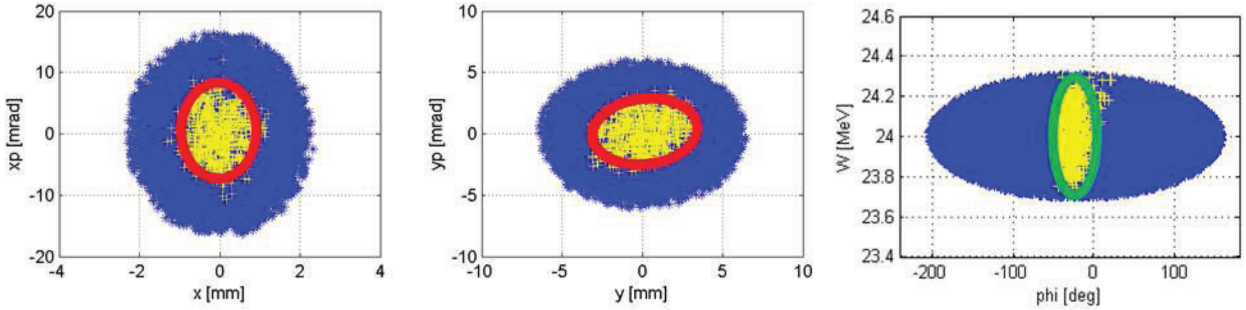

Figure 3: Acceptance plots of the TULIP linac. The yellow dots represent the accepted particles in the horizontal (left), vertical (middle) and longitudinal (right) phase space projections.

The gradients of the PMQs are chosen in such a way to obtain a phase advance per focusing period decreasing from 80 down to 40 degrees, thus allowing the transmission of beams with energies down to 70 MeV through the FODO channel. The use of only two tanks per unit allows to keep the energy spread of the outcoming beam below the limit of the 2 mm of distal fall-off (Fig. 4).

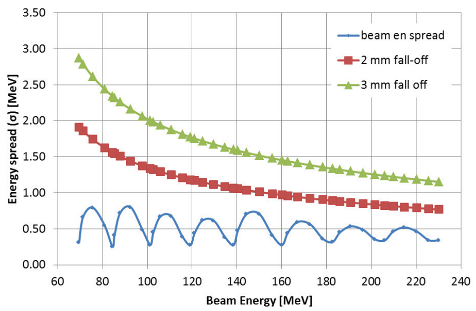

Figure 4: Output beam energy spread obtained from LINAC simulations.

Beam Line Design

The beam line from the end of the linac to the patient has been calculated with the codes TRACE3D and TRAVEL. It consists of a double bend achromatic system and 4 quadrupoles. The first bending magnet is being designed in collaboration with CERN Normal Conducting Magnet group as a C-shaped dipole with 1.42 m radius and a bending angle of 53 degrees. The line has a momentum acceptance of nearly 2%, which allows to obtain a fast range variation of the dose into the patient of ± 7% , i.e. ± 14 mm at a 200 mm depth. Two scanning magnets are added to obtain a transverse treatment field of 20x20 cm^2.

SUPPORTING STRUCTURE DESIGN

The mechanical design of the gantry features a modular and light weight supporting structure with a triangular section girder. The supporting elements are divided in 5 modules (1 for the linac and 4 general supports) allowing for independent assembly and pre-alignment of the linac, that can be carried out at an external facility. The elements of the support girders needed for resistance are also used for the magnets support and to transport ancillaries (cooling, vacuum, electronics). The case is stripped of any useless elements, making possible inspections and position controls at any time. The actuation system foresees the use of counterweights in order to reduce the power needed during rotation. The overall weight of TULIP is about 70 tons, all components included: linacs, magnets, support structure, counterweights and ancillaries.

SUMMARY

A single room facility for protontherapy based on the cyclinac concept has been fully designed. The linac is 11.4 meters long, consumes 150 kW and, mounted on a structure which can rotate by 220 degrees around the patient, can produce fast active energy modulated beams of few nA in the range from 70 to 230 MeV. The unique beam properties of TULIP makes it suitable for active spot scanning technique with tumor multi-painting, the best treatment modality available for protontherapy.

ACKNOWLEDGMENT

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