STUDY OF THE DYNAMICS IN A LINAC BOOSTER FOR PROTON THERAPY IN THE 30-62 MEV ENERGY RANGE

V. G. Vaccaro, M. R. Masullo, S. Lanzone, INFN and University of Naples – ITALY
T. Clauser, A. Raino', V. Variale, INFN and University of Bari – ITALY
C. De Martinis, D. Giove, M. Mauri, INFN and University of Milan – ITALY

Abstract

Recent results in accelerator physics have shown the feasibility of a coupling scheme between a cyclotron and a linac for proton acceleration. Cyclotrons with energies up to 30 MeV, mainly devoted to radioisotopes production, are available in a large number of medical centres. These two evidences have suggested the idea to study and design a linac booster able to increase the initial proton energy up to the values required for the treatment of tumors, like the ocular ones. One of the main challenges in such a project is related to meet the requirement of having sufficient mean current for therapy from a given injection current coming from the cyclotron. In this paper we will review the rationale of the project in order to optimize the transmittance and to minimize the duty-cycle. In this frame we will discuss the basic design of a compact 3GHz linac, from 30 to 62 MeV, with a new approach to the cavities used in a SCL (Side Coupled Linac) structure (PALME project).

INTRODUCTION

The ballistic characteristics of protons and light ions, combined with the well-defined dose distribution at the range end (Bragg peak) and with an appropriate control of the beam energy, make possible to obtain an excellent radiotherapeutic dose conformation to the target. For these reasons hadrontherapy is particularly suitable for tumours which are close to noble organs [1,2].

About 41,000 patients have already been treated world wide with proton beams up to January 2005.

The research development on the coupling scheme between a cyclotron and a linac for proton is well described in various sources [3-5]. In particular the reader may refer to reference [6] to get information about the main aspect of the PALME project.

The starting point of the analysis is the RF design of the cavities [5] Some geometrical parameters, as the septum thickness and the nose geometry, have been settled by resorting also to a thermal analysis Allowing for a mean field E_0 at the gap of 20 MeV/m we get all the cavity parameters and the main e.m parameters. For a bore radius of 4mm, the shunt impedance ranges between 46.1 – 68.2 MΩ/m (30-62 MeV) for a 4% coupling, the Transit time factor is = 0.82 and the Bravery factor is 1.9.

GOALS OF THE DESIGN

A reasonable value of the beam mean current required for the protontherapy is of 8 nA, which is a small amount compared to the usual cyclotron average current. This value can be obtained with a duty cycle of the order of some thousandths. The reduction of the duty-cycle is a goal of the optimization because it will lead to the reduction of the thermal rise on the cavity noses.

Starting from the beam mean current, we defined three requirements for the optimization of the linac design:

- maximise the transmittance, relevant to the useful range of energy, in order to minimize the current required from the cyclotron;
- verify that the beam losses are compatible with safety requirements;
- adjust the duty-cycle in order to keep the thermal rise inside a range acceptable for the tuning

The achievement of these requirements is obtained by means of an appropriate iterative sequence on the linac cavity structure.

ANALYSIS OF THE DYNAMICS

We define the partial transmittance, T_p, which is the ratio between the amounts of extracted useful particles (within the energy spread useful for the therapy) and injected ones. It is also important the overall transmittance, T_t, relevant to the total amount of extracted particles. One of the goal is also to keep the former quantity as high as possible and as close as possible to the latter one.

In order to maximize the transmittance of the linac and to investigate the limits of the longitudinal and transverse acceptance of our structure a detailed work on the transverse and longitudinal dynamics has been performed.

Conservative data on the incoming beam from a 30MeV cyclotron have been used studying solutions with continuous and pre-bunched beams.

We allow for a cyclotron exhibiting rather large beam emittances in both planes with a large energy spread. Therefore, we used an incoming beam with a transverse emittance , $\varepsilon_x = 39\ \pi$ mmrad -- $\varepsilon_y = 20\ \pi$ mmrad, and an energy spread of +/-300 keV.

These figures seem to be reasonable since at least some commercial cyclotrons have parameters close to the quoted ones.

The three requirements are conflicting: indeed a larger transmittance can be obtained by increasing the bore radius; this will imply a decrease of the shunt impedance and as a consequence a lesser power efficiency. This may be compensated by feeding with a higher RF power but this will produce a larger thermal rise on the nose. This behaviour lead us to resort to the variation of other parameters for the transmittance increase, such as the focusing system, the initial synchronous phase.

In this analysis the optimization by working on the focusing system imposes also the change in the number of cells per tank. We still keep constant E_0

For a continuous incoming beam we get the optimum transmittance with a synchronous phase ϕs =-23°.

The quad arrangement has been optimised looking for the maximum transmission value at the last tank (62 MeV). The optimum configuration has 12 tanks, composed by 12 accelerating cavities, and quads long 33.5 mm with a gradient of 195 T/m. This linac is a 10% longer than the one proposed in ref[5].

We got a T_t = 12% and a T_p (@ 1MeV) = 11.6%. The behaviour of the transmittance (T_t, T_p) has been investigated up to 112 MeV (26th tank) and it behaves to reach the asymptotic value (T_t) of 11% for at 13th tank (see Fig. 1) and of 10% for T_p.

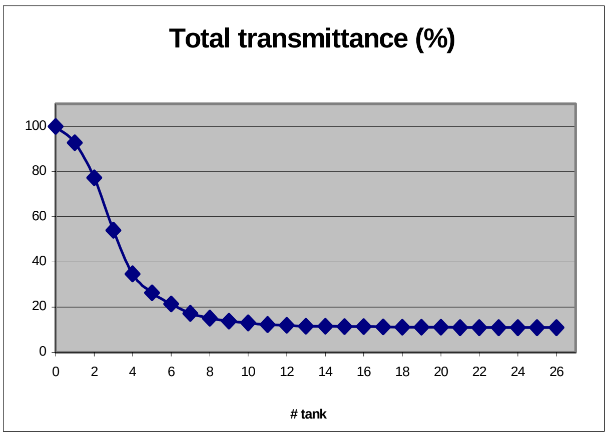

Figure 1: Total transmission as function of #tanks.

Lowering the energy spread does not give remarkable improvement: Δe= 28keV gives Tt =13.3%.

Allowing for the possibility of a pre-buncher we studied total and partial transmittances for different values of the synchronous phase angle ϕs and of the bunch length $2\Delta\phi$, up to the 28th tank (roughly 120 MeV). The structure with quads of length of 33.5 mm and 195 T/m gradient gives the best results, reported in Table 1, where Tt is on the total beam (200MeV), Tp for 1 MeV at the maximum energy.

Table 1: Transmission results for a bunched beam

	ϕs, Δϕ and quad	**Tt @62MeV tank 12**	**Tp**	**Tt @120 MeV tank 28**	**Tp**
1	-23°, 42°	16.8%	16%	14.8%	13.9%
2	-23°, 45°	17%	16.2%	14.9%	14.0%
3	-23°, 50°	16.7%	16.%	15%	14.1%
4	-19°, 45° (190T/m, lq=31mm)	14.7%	13.4%		

The first three cases are almost equivalent showing that the bunch length can vary in a range of values without an appreciable variation of the transmittance. For all cases the total transmittance fast reaches its asymptotic value at roughly the same tank, #16. The parameters T_t and T_p assume almost the same value at the 28th tank indicating that most protons have a final energy well inside a spread of - 1MeV at the maximum. As a consequence the Bragg peak is very well defined as required for a good proton therapy.

It is difficult to decide which the best case. In principle, since the (T_t-T_p) is constant one could decide for the third case. However the final decision could be taken only with the results of the studies up to the final energy.

The last case shown in Table 1 has lower transmittances, but for it the energy of 62 MeV is reached with a linac long 3.07 m instead of 3.33 m of the other cases. The gain in the length doesn't worth a lowering of the transmission.

With a partial transmission at 62 MeV of 16% (14.1% at 120MeV) and a beam duty cycle of 0.1% we get a trapping efficiency of $16x10^{-5}$ ($14.1x10^{-5}$).

The transmission could be furtherly increased by means of a reduction of the incoming beam emittances. Collimator system could be implemented. As an exercise we analysed the case $\varepsilon x = \varepsilon y = 20\ \pi$ mm mrad obtaining T_t = 16.7% , T_p =16.2 %, for the continuous beam, and T_t = 24.2%, T_p 23.2 %, for the bunched case (3) of Table 1.

ACTIVATION STUDY

As previously mentioned, the optimization of the linac design as to take into account the beam losses along the machine which during accelerator operations lead to activation of the components. Shielding materials and environment, ground water and air are activated as well. It is important to evaluate if losses are compatible with safety requirements and consequently which is the most effective apparatus for the protection of people and environment as well as radiation sensitive equipment used in the accelerator construction.

During the PALME design the activation process in the structure has been studied in order to evaluate the related dose rate. The goal of this analysis was to define maintenance procedures whenever the dose rate coming from the components would be noticeable.

The dynamics analysis, reported in the previous paragraph for the real compact structure of PALME, (where we obtained distributed losses of nearly 90% in the injected beams due to interaction with the internal walls boundaries) suggests us to restrict our studies to the process of interaction of the primary 30 MeV beam with the copper RF cavities.

Cu-63 (69%) and Cu-65 (31%) are the main isotopes present in the copper. Taking into account the cross-section and the energy threshold, we have identified the following subset, among all the possible reactions between these isotopes and protons:

Cu-63: → Cu-63(p,n)Zn-63, Cu-63(p,2n)Zn-62, Cu-63(p,3n)Zn-61, Cu-63 (p,p2n) Cu-61

Cu-65: → Cu-65(p,n)Zn-65, Cu-65(p,3n)Zn-63, Cu-65(p,pn)Cu-64

0-7803-8859-3/05/$20.00

To study the process we adopted a quite pessimistic scenario where:

- the beam at the injection interacts in a small area
- the accelerator operation mode is continuous for a time larger than that required to reach saturation for all the nuclear products of interest
- the injected beam current is 100 nA (which is a factor 10 more than the previously estimated required current for patient treatment).

The beam interaction area results in a point like source whose activity has been computed using the formula:

$$A_s = N \int I(x) \cdot \sigma_i(x) \cdot dx \qquad (1)$$

where *As* is the total activity (in Bq) at saturation, *I* is the beam current (protons/sec), *N* is the copper density (atoms/cm^3), σ is the cross of each reaction (mb), *x* is the penetration depth in the copper.

Formula (2) gives the dose evaluated taking into account only the gamma ray decay coming from this source:

$$D = \frac{A}{4\pi d^2} \sum_i n_i E_i \mu_i \qquad (2)$$

with *D* the dose (Gy), *A* the total activity (in Bq), *d* the distance between the source and the evaluation point (this value has been fixed to 1m), μ the tissue absorption coefficient (g/cm2), *ni* and *Ei* respectively the production yield and the energy (in J) of each emitted gamma.

The results obtained are summarized in Table 2 and in Figure (2).

CONCLUSIONS

Allowing for the found trapping efficiency of 14.1x10^{-5} and requiring for proton therapy an average linac current of 8 nA, we may need a cyclotron peak intensity of 57 µA. This current is attainable for the largest majority of cyclotrons. As a consequence the duty cycle can be kept to this value or to values even lower according to the maximum current available from the cyclotron. A lower duty cycle will produce a smaller thermal rises on the noses and, as a consequence, a smaller detuning of the cavities.

The maximum amount of dose rate at saturation is given by Zn-63 , but because of its short half life, it becomes quickly negligible. One may easily calculate the total dose rate, after 3.0 hrs from the beam stop event; this falls to a value of the order of 100 µGy/h which is compatible with the possibility of carrying out a maintenance procedure.

Table 2: Dose for present nuclides

Nuclide	*Half life*	*Dose rate at sat. (µGy/h)*
Zn61	89s	0.12
Zn63	38m	140
Cu61	3 h	12.6
Zn62	9 h	16.2
Cu64	13 h	19.0
Zn65	244d	32.6
Total		220

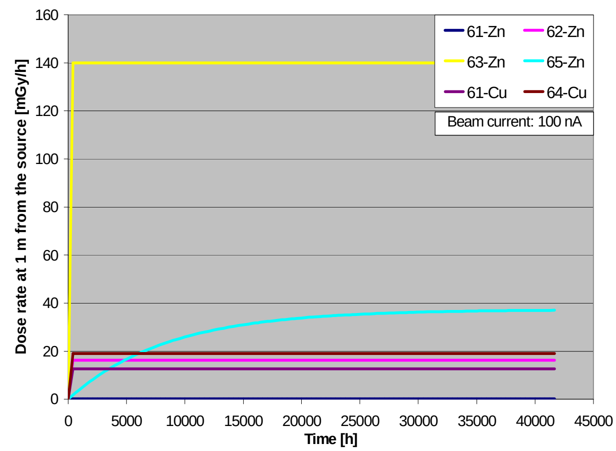

Figure 2: Dose rate as function of time.

REFERENCES

[1] "European Strategy for Cancer Research" Commission of European Communities DG XII-Medical Division (1991): XII/F-6-AV/nv/91001P

[2] Particles NewsLetter (PTCOG) n. 35, January 2005, pag 10 - Edt: Janet Sisterson Ph.D., NPTC

[3] U. Amaldi et alii, "LIBO - A 3 Ghz proton LInac BOoster of 200 MeV for cancer treatment" Proc. XIX International Linac Conference, Chicago, 1998

[4] U. Amaldi et alii, " LIBO – A LInac-BOoster forProtontherapy: Construction and Test of a Prototype " NIM A, 521 (2004), 512.

[5] V.G.Vaccaro et alii «Study of a linac booster for Proton therapy in the 30-62 MeV energy range" Proc. of the EPAC04 – Lucerne July 2004

[6] V.G.Vaccaro et alii «Some relevant aspects in the design and construction of a 30-62 MeV linac booster for proton therapy " LINAC04 –Lubeck August 2000