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

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Abstract

Recent results in accelerator physics have shown the feasibility of a coupling scheme between a cyclotron and a linac for proton acceleration: a 60MeV proton beam has been successfully captured and accelerated by a prototype module (LIBO) of a 3GHz linac. While the number of 60MeV cyclotrons is limited, a large number of 30MeV ones, mainly devoted to radioisotopes production, is available in medical centres. These two evidences have suggested the idea to study and design a 30MeV linac post-accelerator able to bridge the gap between the 30MeV commercial cyclotrons and the 60MeV LIBO. The main challenge in such a research project is related to meet the requirements arising from the beam dynamics with the constrains due to the mechanical structures and tolerances and to the heat dissipation mechanism chosen in the design. In this paper we will review the rationale of the research project and we will discuss the basic design of a compact 3GHz linac with a new approach to the cavities used in a SCL (Side Coupled Linac) structure.

INTRODUCTION

The role of hadron beams (protons and light nuclei) in radiotherapy is becoming more and more catching on in comparison with the conventional therapy with photons and electrons for several kind of tumours. This is especially true when one considers that the aim of any tumour therapy is to cure it minimising the side effects in the critical surrounding organs. 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 dose conformation to the target. For these reasons hadrontherapy is particularly suitable for tumours which are close to noble organs [1,2].

More than 36.100 patients have already been treated world wide with proton beams up to January 2004. The therapeutic activity, which was beforehand mainly concentrated around nuclear physics laboratories, is now moving to ad hoc conceived hospital units [3,4]. The idea of using a compact proton linac at 3 GHz for hadrontherapy was born at the beginning of 90s by TERA Foundation. In 93 the first design of a 3 GHz proton linac was carried out inside a collaboration between TERA and ENEA. The first LIBO studies were based on the specification of the Clatterbridge cyclotron (where in 92 a 1.3 GHz proton linac was considered as a booster for the 62 MeV cyclotron [5]).

In Italy during 1999, a collaboration between Italian Institutions and CERN was born aiming to design a 3GHz Side Coupled Linac (SCL) booster for low energy protons from 60MeV to 220MeV [6,7]. The first module (LIBO) of this project from 62 to 74MeV, has been designed, built and successfully tested [8,9]. LIBO tests fully demonstrated the working principle of an SCL for protons from 62 to 73MeV. It was shown that accelerating gradients higher than the nominal value of 15.8MV/m (with a peak power of 4.7MW) could be achieved without multipactoring and with few breakdown events (an accelerating field level of 27.5MV/m was reached with the maximum peak power available of 14.2MW). The corresponding bravery factor was 2.6 (namely the peak value of the electric field reached 2.6 times the Kilpatrick limit), the design one beeing roughly 1.6 [10].

The feasibility of the mentioned prototype enlarged the application area of these accelerators towards lower energies and more compact structures [11].

On the base of the excellent results and with the experience of LIBO, a group of us started a new experiment (PALME financed by Istituto Nazionale di Fisica Nucleare) for designing a 3GHz linac able to accelerate proton beams delivered by existing cyclotrons of 30MeV and for building the first module (30-35MeV), named MOD30. This initiative would be an important step in the direction of integrated system of nuclear medicine and proton-therapy.

This idea was strengthened by the fact that in the world several centres exist which are already equipped with proton cyclotron of 30MeV for isotope production in nuclear medicine and for imaging techniques (much more than those equipped with 60MeV) or are going to. With a 30MeV injection energy booster connected to their cyclotrons these centres could extend their activities to the deep seated cancer therapy with investments lower than those required for separate installations with the same functions. Indeed, this lower energy linac could not only bridge the gap between 30MeV cyclotrons and 60MeV linac (LIBO like), but also could be used alone to boost the proton energy up to the values required for the treatment of non-deep tumours, as uveal melanoma (62MeV).

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THE PARAMETRIC ANALYSIS

PALME structure (Fig.1) is similar to LIBO. It consists in five modules; differently from LIBO, each module is formed by only two tanks and two bridge couplers. Each second (green) bridge coupler is the gateway for RF.

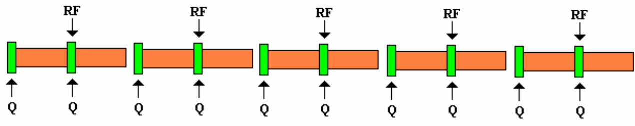

Fig.1: Sketch of PALME structure.

The cavity shape has been studied by means of Superfish code at the nominal frequency of 3GHz. The design foresees a peak surface field such that the bravery factor is 1.9 times the Kilpatrick limit, with an mean axial field value of E=20MV/m. The behaviour of the coupled cavities has been studied by means MWS Studio. The quality indices to optimise the cavity behaviours are the shunt impedance (Z) and the thermal rise (ΔT) of the nose in the cavity. This analysis was done resorting to Ansys and Superfish codes, as function of the septum thickness (s) and the nose cone angle (α_c). By using the values shown in Tab.1 for the diameter (D), gap length (g), bore radius (R_b) and a duty cycle of 0.2%, we have the behaviour for Z and ΔT, as shown in Fig.2.

Table1: Cavity parameters

D=6.7 cm	g= 0.422 cm	R_b =0.4 cm

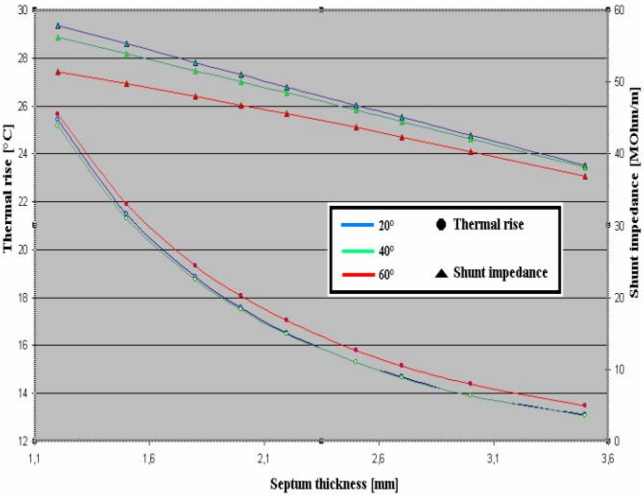

Figure 2: Shunt impedance and thermal rise as a function of septum thickness.

In general the major constraint comes from the thermal rise. It is advisable to stay below 10°C, in order to get an acceptable detuning. The thermal rise is proportional to the duty cycle. The final choice of the optimal parameters will be done in connection to the parameter specific values of the upstream cyclotron.

DYNAMICS ANALYSIS

In order to keep the energy spread of the beam into acceptable values for radiotherapy (±0.6MeV), the stable phase was set to φ_s=-18°. The distance (L) between the centres of accelerating cavity (AC) should match in length the space covered by particles in half a period (π/2 mode). Therefore the length L varies along the structure. However, since the energy gain per tank is small, we may take the mean value of L in the tank. In the case of MOD30 it is for the first and second tank respectively L=1.26cm and L=1.31cm.

The longitudinal dynamics calculations give the values of parameters as shown in Table 2.

Table 2: PALME main parameters; MOD30 in yellow boxes

	Mod 1	**Mod 2**	**Mod 3**	**Mod 4**	**Mod 5**
Accel. Cells	**13+13**	**13+13**	**14+14**	**14+14**	**15+15**
Quad:L_1+L_2 (mm)	**176.38**	**190.14**	**203.90**	**218.13**	**232.05**
$\mathcal{E}_{output}$ (MeV)	**35.27**	**40.94**	**47.46**	**54.40**	**62.28**
<Grad> (MV/m)	**10.3**	**10.3**	**10.5**	**10.5**	**10.7**
Mean field at gap <Ez>=20MV/m **ε_l=442 π rad keV**					**φ_s=-18°** **Total length =3.078m**

The transverse acceptance depends on the field gradient (B’) of the permanent magnetic quadrupoles (pmq), and on their efficient lengths (L_{eff}) and on the geometrical parameters shown in Tab.1 and 2. We assume that it is possible to get pmq’s with a field gradient B’ up to 190T/m [12]. Taking as variable parameter L_{eff} and B’, we obtain the acceptances and the Twiss angles listed in Tables 3 and 4.

Table 3: MOD30 acceptances (scaled to πmmmrad)

B’(T/m) L_{eff}(mm)	180	185	190
31	**A_x=87.0**	**A_x=97.0**	**A_x=107.4**
	A_y=13.6	**A_y=13.8**	**A_y =13.9**
32	**A_x=97.6**	**A_x=108.8**	**A_x=117.6**
	A_y=13.8	**A_y=13.9**	**A_y=13.8**
33	**A_x=109.6**	**A_x=123.1**	**A_x=137.9**
	A_y=13.9	**A_y=13.8**	**A_y=13.6**

Table 4: MOD30 Twiss parameters

B’(T/m) L_{eff}(mm)	180	185	190
31	**β^+=1.179**	**β^+=1.161**	**β^+=1.154**
	β^-=0.184	**β^-=0.165**	**β^-=0.149**
32	**β^+=1.159**	**β^+=1.153**	**β^+=1.157**
	β^-=0.164	**β^-=0.147**	**β^-=0.132**
33	**β^+=1.152**	**β^+=1.157**	**β^+=1.174**
	β^-=0.146	**β^-=0.130**	**β^-=0.116**

The trasmittance of the linac, which indicates the ratio between the outgoing and ingoing particles in the accelerator, is an important parameter to investigate. We assume for the injected beam the following transverse emittances, $\varepsilon_x=20\pi$mmmrad and $\varepsilon_y=39\pi$mmmrad, and an energy spread of 300keV. We assume that transverse emittance of the injected beam can be properly matched to the transverse acceptance of the linac.

From these values we may calculate the total trasmittance (T_t) and the partial trasmittance (T_p) at (62.75±0.5)MeV which are shown in Table 5.

Table 5: Parametric analysis of the trasmittances

B'(T/m) L_{eff}(mm)	180	185	190
31	T_t =4.3%	T_t=4.5%	T_t=4.6%
	T_p =5.2%	T_p=5.2%	T_p=5.0%
32	T_t=4.5%	T_t=4.6%	T_t=4.4%
	T_p=5.2%	T_p=5.0%	T_p=4.6%
33	T_t=4.6%	T_t= 4.4%	T_t=3.9%
	T_p=5.0%	T_p=4.6%	T_p=4.0%

As expected the trasmittances are constant for a constant value of the product $B'\cdot L_{eff}$. Example: cyclotron current of 170μA, duty cycle of 0.1% and $B'\cdot L_{eff}$=5.82T (yellow boxes), we may get a sufficient output current (7.8nA) for therapy; in this situation we have also a "dirty" current (inefficient for therapy) smaller than 0.6nA with a large energy spread below 62.25MeV. Increasing the cyclotron current the optimum may move towards higher values of the product $B'\cdot L_{eff}$, where we may get a smaller percentage of dirty current. Once the value of $B'\cdot L_{eff}$ is chosen, it is convenient to take L_{eff} as large as possible. With the values given above we may set the septum dimension to 1.8mm. The thermal rise will stay below 10°C (see Fig.2). This choice implies a relatively high shunt impedance. With this value of shunt impedance the Tab.2 should be completed by the following values of feeding power (Table 6):

Table 6: Feeding power per tank; MOD30 in yellow box

2.81MW	**2.72MW**	**2.87MW**	**2.83MW**	**3.01MW**

CONCLUSIONS

In this paper we showed the rationale of PALME project, the goal of which is to design a linac for protontherapy as compact as possible in order to fit it in a medical structure, and to realize the first module (MOD30).

A parametric study is a good guidance for the definition of the final design parameters. The parameters should be set by means of a good balance between several kinds of needs. A first kind of constraints comes from the radiotherapy requests: a certain value of maximum energy spread, value of the final peak current, beam behaviours, etc. Other ones depend on several technical needs, as cost reduction of the RF system (high shunt impedance); minor detuning at variable RF power (small thermal rise); high accelerating gradient to get more compact the longitudinal dimension but not extreme bravery factor. All these needs must be also matched with the specific parameter values of the upstream cyclotron.

PALME project is in a quite advanced state. As shown in the previous, all of these parametrical analysis was done. In such a way we were able to fix some cavity geometrical parameters in order to start machining and brazing tests. Both were successful.

The only free parameters of our analysis were the injecting ones. In the next future we will set the injecting cyclotron and we will fix the last parameters in order to start the construction of MOD30.

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