OPTIMIZATION DESIGN OF A SIDE COUPLED LINAC (SCL) FOR PROTONTHERAPY: A NEW FEEDING SOLUTION

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Abstract

It is proposed to use a Side Coupled Linac (SCL), starting at 30MeV, up to 230MeV for protontherapy. The linac consists of 25 modules (two tanks each). Twelve 3GHz power generators feed two modules each in parallel and one power generator feeds the last module. The SCL is designed, assuming a mean accelerating field in the cavities of 16,5MV/m. The longitudinal and transverse beam dynamics have been studied, assuming that the input parameters emittance, energy spread and mean current are those of commercial 30MeV cyclotrons. The characteristics of the output beam were analysed: the transmittance value is largely sufficient to deliver a correct dose for therapy; the beam line activation is kept largely below allowed levels; the output energy spread is sufficiently small. The first prototype module is under construction and a second one is under design. Contacts with e2v have been established for defining an agreement, which foresees to use magnetrons as feeders for the acceleration tests. Attention was therefore paid to phase locking constraints among feeders. Theoretical studies suggest that transmittance is not significantly affected if de-phasing is kept into values that seem attainable with phase-locked magnetrons. A first investigation was performed on the possibility of resorting to a 18MeV cyclotron. The results were stimulating.

INTRODUCTION

The potential of proton cancer therapy is now widely accepted. It has already been identified by an EU working group as deserving of priority support [1]. About 43.000 patients [2] have already been treated worldwide with protons beams up to July 2005. The therapeutic activity, which was beforehand mainly concentrated around nuclear physics laboratories, is now moving to ad hoc conceived hospital units. In 1983, when in Tsukuba (Japan) a nuclear physics facility was converted in a medical centre, the radiotherapy with protons started to be performed in a centre devoted only to medical purpose. Since then many hospital based centres have been developed mainly in the USA and Japan [2,3,4].

In Italy this activity started with the TERA project in 1991 thanks to the INFN financial support [5]. After this, the TERA Foundation stimulated the interest of many University and Laboratory researchers around the hadron therapy project. This activity has created relationships and synergies among researchers belonging to TERA, INFN, ENEA and Italian Universities, covering rather broad fields from accelerators, to radio-biology, dosimetry, detection and telematics, etc. In this frame a growing interest arose around the realisation of new and compact accelerating structures.

Two experiments have to be mentioned: LIBO and PALME, both based on the idea of using a compact proton Side Coupled Linac (SCL) at 3 GHz for boosting the proton energy up to values sufficient for deep therapy. The use of linac exhibits some interesting peculiarities as the modularity, the energy modulation without resorting to absorbers, the possibility of being used as a booster for accelerators conceived for other applications. The accelerating system consists in a cyclotron followed by the SCL.

The first LIBO studies were based on the specification of the Clatterbridge cyclotron (where in 1992 a 1.3 GHz proton linac was considered as a booster for the 62 MeV cyclotron [6]). The first module (LIBO) of this project from 62 to 73MeV, has been designed, built and successfully tested [7]. 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) [8].

The feasibility of the mentioned prototype enlarged the application area of these accelerators towards lower energies and more compact structures. The PALME experiment [9] (financed by Istituto Nazionale di Fisica Nucleare and the by the Italian Ministry of Scientific Research) was conceived with the aim of designing a 3GHz linac able to accelerate protons delivered by existing cyclotrons of 30MeV and of 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, because the linac could be installed in centres already equipped with proton cyclotron of 30MeV used for isotope production in nuclear medicine and for imaging techniques. 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).

Studies performed during the PALME experiment showed that the accelerator performances improve very much by lowering the longitudinal mean electric field.

Even if the price for this fact is the lengthening of the accelerator, the connected benefit is largely compensating. A minor warming-up of the accelerating cavity noses is a first advantage, to which follows as a consequence a minor frequency shift of the cavities; this effect simplifies the cavity tuning procedure. A second benefit comes out from the increment in the capture efficiency and in the beam transmission: the reduced electric field produces a minor de-focusing of the beam with a positive influence on the transverse dynamics. This behaviour may allow the use of injectors (cyclotrons at 30MeV) of more modest performances in terms of output current, and likely less expensive. Furthermore, it is possible to foresee other advantages, as the possibility of pushing down the linac injection energy (e.g. 18MeV) in order to use cyclotrons even less expensive.

From this idea the ACLIP project was conceived for studying and optimizing a 3GHz SCL from 30 to 62 MeV. The optimization did not neglect the economical aspects. Among the others the reduction of the costs relevant to RF feeders has been assessed. To this end it is believed that replacing klystrons with magnetrons may give a substantial contribution.

THE STRUCTURE: DYNAMICS STUDY

In order to understand the feasibility of such a linac with an injection energy of 30 MeV, we focalised our initial studies on two machine characteristics:

- the behaviour of the machine transmittance, which indicates the ratio between the outgoing and incoming particles in the accelerator.
- the power requirement for each tank in order to optimise the generator configuration and to reduce their costs.

In this optics, the cavity shape has been studied by means of Superfish code at the nominal frequency of 3GHz. The design foresees a mean axial field value of E=16.5MV/m (this corresponds to a maximum surface electric field 1.5 times the Kilpatrick limit). The shunt impedance is about 31 MΩ/m for a 4% coupling (at 30MeV).

The resulting ACLIP structure is about 3.6 m long and consists of six modules, each one formed by two tanks and two bridge couplers (see Fig. 1). Quadrupoles are located in the bridges and each second bridge is also used for the feeding system.

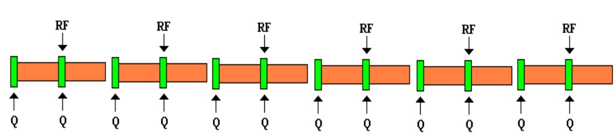

Figure 1: ACLIP layout.

The distance between the tanks varies according to the particle velocity and it is set to a value of 3.5 $\beta\lambda$, meanwhile the module distance may be fixed constant to its allowed minimum of 95 mm. The magnetic field gradient (B') and the effective lengths (L_{eff}) of the permanent magnet quadrupoles (pmq) have been varied in order to optimise the transverse acceptance on which depends the beam transmittance. For the final simulations we used the following values: B'=190 T/m and L_{eff} = 32mm.

In the proposed configuration the power requirement for each tank results to be less than 1MW. This fact allows four tanks (two modules) to be coupled together into one RF unit of 4MW.

For the dynamics studies, we used an input continuous beam, whose characteristics have been extracted from the data sheet of a commercial 30MeV cyclotron. An energy spread of 150keV, a transverse normalized emittance of 10π mm mrad and 5π mm mrad in the horizontal and vertical plane respectively have been assumed.

We have evaluated the total and the useful beam transmittances T_0; the latter being defined as the amount of transmitted particles in a window of 2MeV centred at the energy where the particle density is at a maximum. This window is sufficiently small for radiotherapy.

The results obtained with the mentioned configuration are shown in Table 1.

Table 1: Beam transmittances at 62MeV final energy

Input Energy	**T_0**	Total	Useful
30 MeV		8.4 %	8.18 %

As ACLIP is only the first part of a linac that should attain the energy of 230MeV, we believed that it was necessary to make at least a preliminary investigation on the whole linac devoted to deep proton-therapy. This second part of the accelerator was designed in a way similar to the first one. The parameters of the whole linac are summarised in Table 2.

Table 2: 30 - 230MeV Linac parameters

Total Length	20 m	**Module Number**	25
Tank Number	50	**Feeder Number**	13
Feeder Power	< 4MW	**PMQ Integrated Gradient**	6.1 T

Even if the design was not optimised, the values of the transmittances are more than reassuring as shown by the figures reported in Table 3.

Table 3: Beam transmittances at 230MeV energy

Input Energy	**T_0**	**Total**	**Useful**
30 MeV		7.78 %	7.1 %

Assuming an input current of about 100 μA and a beam duty-cycle of 0.1%, the values of the transmittances are sufficient to deliver a correct dose for therapy at 62 MeV and 230 MeV. In addition to this, the beam line activation is kept largely below allowed levels [9] and the very small difference between the total and useful transmittances indicates the good quality of the beam.

A thermo-mechanical analysis was performed assuming the thermal load due to ohmic dissipation for the conservative RF duty-cycle of 0.2 %. The detuning due to the thermo-mechanical deformation is smaller than 150kHz.

The good results obtained for the 30MeV case suggested to investigate the behaviour of a linac similar to ACLIP, but with a lower injection energy (18MeV). This choice may allow the use of less expensive injection cyclotrons, already present in several radiotherapy centres. The 18-30MeV linac consists in four modules for a total length of roughly 1.7m. The shunt impedance is about 20MΩ/m for a 4% coupling (at 18MeV).

By using the same mean field and input beam parameters, an initial analysis (from 18 to 230 MeV) gives the transmittances reported in Table 4.

Table 4: Beam transmittances at different final energies

Input Energy	**T_o**	**@62MeV**	**@230MeV**
18MeV	Total	7.04 %	6.82 %
	Useful	7 %	6.52 %

Assuming the same input current and same duty-cycle as before, the values of the transmittances are sufficient to deliver a correct dose for therapy at 62 MeV and 230 MeV.

THE RF POWER GENERATOR SYSTEM

Contacts with e2v technologies (Chelmsford, U.K.) have been established for defining an agreement, which foresees the employment of magnetrons as feeders for the acceleration tests.

In order to ensure the synchronisation with the beam, great attention has to be paid to phase locking constraints among feeders. It is assumed that the de-phasing values can be kept within the interval ±1.5deg.

For a synchronous phase ϕ =18°, the total and useful transmittances as a function of de-phasing ($\Delta\phi$) have been analysed for the complete structure up to 230MeV. A random de-phasing was added to the phase of all modules fed by a single magnetron. A statistical evaluation was performed for a uniform distribution in the interval ±1.5deg. The results, at 62MeV and 230MeV, relative to the mean transmittances <T>, normalised to the values T_0 with no de-phasing, are reported in Table 5.

Table 5: Transmission data for a de-phasing of 1.5deg.

ΔΦ= 1.5deg		@62MeV	@230MeV
Total	$<T>/T_o$	98.7%	96.1 %
Useful	$<T>/ T_o$	98.2%	96 %

We see that the degradation of the beam quality (useful current intensity and energy spread) can be kept within acceptable values for cancer therapy.

CONCLUSIONS

The first module of the ACLIP structure will be completely machined by the end of July. The brazing process has been extensively studied and tests have been carried out on a five cells prototype to qualify the procedure and the design of the relevant mechanical features. The first module brazing will be done at CERN before the end of this summer.

After the brazing the module will be fully qualified with an extensive study of the low power behaviour.

During autumn 2006 the module will be transferred and installed at the headquarters of e2V technologies in U.K. where high power tests will be conducted. The RF power feeding scheme, along with the required test measurement facilities have already been discussed with e2V. The test enclosure and major components are already available.

Acceleration tests are foreseen in the next year at Laboratori Nazionali del Sud (LNS) of INFN in Catania. Beam time has been already allocated by the LNS-PAC.

A second module will be designed, fabricated and submitted to same tests as the first one. In addition acceleration tests are foreseen with the two modules in cascade. This test will give a better definition of the accelerated bunch and will prove the principle of magnetron phase-locking in beam acceleration.

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