SOME RELEVANT ASPECTS IN THE DESIGN AND CONSTRUCTION OF A 30-62 MEV LINAC BOOSTER FOR PROTON THERAPY

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Abstract

Recent results in accelerator physics showed the feasibility of a coupling scheme between a cyclotron and a linac for proton acceleration. Cyclotrons with energies up to 30MeV, mainly devoted to radioisotopes production, are available in a large number of medical centres. This suggested to design a linac booster able to increase the proton energy up to 62MeV as required for treating tumours like the ocular ones. In this paper we will discuss the basic design of a compact 3GHz SCL (Side Coupled Linac). Among the many challenges of such a project one of the most interesting is the tuning of the cavities. Because the tuning can be done only after assembling the system, it is difficult to detect which cavities are responsible for the detuning: indeed the resonant behaviour of single cavity is lost since the resonances merge into the resonant modes of the whole system. It is shown how, from the measured mode frequencies of the system, it is possible to derive the unknown resonances of each cavity and then refine the tuning. The proposed procedure is quite general and is not restricted to the SCL. This procedure is quite attractive because its use may relax the fabrication tolerances and avoids any bead pull procedure. In addition to this one may foresee even an on line computer driven tuning. Examples were given for 13 cavities fed at π/2 mode.

INTRODUCTION

The effectiveness of proton therapy of deep-seated solid tumours is now well established for the great numbers of the accumulated clinical data since when Bob Wilson proposed this therapy in 1947 in his visionary paper [1].

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 [2]. More than 36.000 patients [3] have already been treated world wide with proton beams of energy ranging between 60MeV to 220MeV, according to the tumour depth. The therapeutic activity, which was beforehand mainly concentrated around nuclear physics laboratories, is now moving to ad hoc conceived hospital units. Only in 1991, with the completion of the LOMA LINDA facility, proton therapy became available in a hospital site. Since then several hospital based centres have been developed [3,4,5].

The idea of designing a linac booster able to increase the proton energy up to values adequate for protontherapy was born at the beginning of 90s. A detailed description of the development of this idea and of its outcome can be found in ref. [6,7]. The PALME project concerns the design of a 3GHz linac able to accelerate up to 62MeV proton beams delivered by existing cyclotrons of 30MeV. Many of these cyclotrons are already in use for isotope production in nuclear medicine. The goal is to achieve a mean energy gradient of 11MeV/m, so that the total linac length should not exceed 3m. With 30MeV injection energy booster connected to their cyclotrons these centres could extend their activities to cancer therapy with investments lower than those required for separate installations with the same functions.

THE ACCELERATOR

The SCL is formed by a chain of large number of accelerating cavities (AC) connected via irises to off-set coupling cavities (CC). The principle which governs the frequency behavior of such a device is the resonant coupling [8]: when coupled, the all equal resonances of the cavities split into the resonant modes of the whole system. Each mode is characterized by the phase advance between adjacent cavities. This implies that when excited, all the cavities resonate on this mode with their own phase advances. Therefore, the peculiar aspect of this configuration is the possibility of having only one RF feeder for a very large number of cavities (almost fifty elements AC+CC). For SCL compact accelerators the RF power frequency is matched to the so called π/2 mode: this means that each second cavity is empty of energy and it has the role of coupling adjacent cavities.

In general the SCL basic bricks are tiles, on the opposite sides of which a half-CC and a half-AC are machined. The fabrication tolerances play a crucial role in the performances of these devices because of the extreme high frequency of the feeder. In fact, the fabrication errors produce deviations from the design nominal values of the most relevant parameters.

Even if we are dealing with devices working in the GigaHertz range, lumped circuit representation very well suits the SCL behaviour [8]. In the next section we resort to the transmission matrix representation of the two-port device for the tiles and we investigate on the overall behaviour of the SCL. In the case of N identical two-port device chain, the whole system exhibits N+1 resonant frequencies, each characterised by its own mode (phase advance). These frequencies are given by simple analytical formulas [9]. The actual situation is quite intricate: after machining the tiles are unequal and the lumped parameter values of the device exhibit slight

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differences from tile to tile; furthermore these parameters, after assembling and brazing the tiles, exhibit additional random errors. At this stage it is impossible to make direct measurements of the single two port device, the only measurement allowed being on the whole system.

THE LUMPED CIRCUIT MODEL

The electromagnetic behaviour of a single tile can be represented by a two-port device made of two lumped resonant series circuits coupled by a coupling coefficient. The overall SCL behaviour is so described by a two-port device chain. The transmission matrix of this chain is studied. Our goal is to study the overall behaviour of a SCL structure in order to find out tools useful for the design, the analysis, the diagnostics and the correction of the single cavities. We consider two-port devices which are similar but exhibit slight differences, essentially due to fabrication errors which produce deviations of the cavity parameter nominal values. We allow for the transmission matrix representation [10], denoting each cavity by the index p. The quantity T_p is therefore defined as:

$$\begin{pmatrix} V_p \\ I_p \end{pmatrix} = \begin{pmatrix} t_{11}^p & t_{12}^p \\ t_{21}^p & t_{22}^p \end{pmatrix} \begin{pmatrix} V_{p+1} \\ I_{p+1} \end{pmatrix} = \mathbf{T}_p \begin{pmatrix} V_{p+1} \\ I_{p+1} \end{pmatrix} \quad (1)$$

We suppose that each two-port device is composed by two lossy resonant series circuits [10] as shown in Fig. 1.

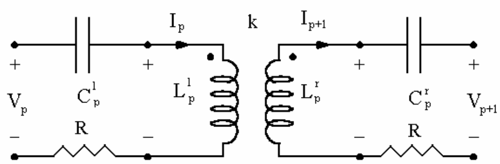

Figure 1: The generic two-port device representing two resonant circuit coupled by a coupling coefficient k.

In this device the parameters differ for different values of p. Furthermore we assume that the r.h.s parameters differ from the l.h.s. ones, as shown in Fig. 1, where the indices *r* and *l* stand for right and left. We may assume that the resistance does not depend on index p.

We may define for each tile two resonant frequencies (the end tiles only one) as:

$$f_p^l = 1/2\pi\left(L_p^l C_p^l\right)^{1/2} \quad \text{and} \quad f_p^r = 1/2\pi\left(L_p^r C_p^r\right)^{1/2} \quad (2),$$

for the l.h.s and r.h.s. of the p-th two-port device, where p=1,.. N+1 for the index l and p=-1,.. N for the index r. Resorting to formulas, which can be found in the literature [8, 9] we get, for lossless all equal devices, the resonant mode frequencies, F_s:

$$F_s = \frac{f_0}{\sqrt{1 + k\cos[s\pi/(N+2)]}} \qquad 1 \le s \le N+1 \quad (3),$$

where f_0 is the resonant frequency of the unperturbed two port device of Fig 1. The quantity sπ/(N+2) is the phase advance of the field along the chain and it is a characteristics of each mode. We are particularly interested in the π/2 mode (s=1+N/2), since of its stability with respect to the errors.

THE PERTURBATIVE MODEL

Consider now a chain of N different two-port devices, where N is an even number. The chain transmission matrix has been studied by means of a perturbation analysis. We look for the resonant frequencies without any restriction to the mode.

The overall transfer matrix is:

$$\mathbf{T}_{tot} = \prod_{p=1}^{N} \mathbf{T}_p \quad (4).$$

. The equation to be solved is [10]:

$$Z_c^l \left(\prod_{p=1}^{N} \mathbf{T}_p \right)_{21} + Y_c^r \left(\prod_{p=1}^{N} \mathbf{T}_p \right)_{12} = 0 \quad (5),$$

where Z_c^l and Y_c^r are the left hand and right hand loads of the chain.

We define the deviation of the resonant frequencies for each cavity as:

$$\Delta f_p = \Delta f_{p-1}^r + \Delta f_p^l \quad (6).$$

From eqs. (5), resorting to perturbative techniques, after some algebra, we get [10] an expression for the perturbed frequency of the modes ΔF_s as a linear combination of the perturbed resonant frequencies Δf_p of the cavities:

$$\frac{\Delta F_s}{F_s} = \frac{2}{(N+2)} \sum_{p=1}^{N+1} \frac{\Delta f_p}{f_0} \sin^2 \frac{ps\pi}{N+2} \quad (7).$$

In the system (7) the equations of indices s and N+2-s, are identical. As consequence, the number of the independent equations is the first integer equal to 1+N/2. This property implies that the system (7) cannot be solved respect to Δf_p. However, defining the new unknown

$$\Delta\bar{f}_p = \Delta f_p + \Delta f_{N+2-p} \quad (8),$$

in the system of equations (7) the number of unknowns ($\Delta\bar{f}_p$) is equal to the measurable quantities (ΔF_s); the determinant of the system is finite; so that eq. (7) can be inverted as:

$$\frac{\Delta\bar{f}_p}{f_0} = \sum_{p=1}^{E\left(\frac{N}{2}\right)+1} A_{ps} \frac{\Delta F_s}{F_s} \quad (9),$$

where $E(x)$ means the minimum integer larger than x.

THE TUNING

It is customary, after a preliminary tuning by means of ad hoc machining, to refine the tuning in order to better equalise and maximise the field. This is done by introducing small pistons in the accelerating cavities (all the cavities) for π/2 mode (π-mode). All pistons are inserted inside the cavity of the same amount. Monitoring is made by means of the bead pull. We will call this method as Uniform Piston Advancement (UPA) tuning.

The proposed tuning, named System Mode Sounding (SMS), consists in: 1) the detection of the mode frequencies, the sounding the system in the frequency band $f_0(1\pm k)$; 2) the calculation of the correction by means of eq. (9); 3) the introduction (extraction) of tuners producing the desired tuning refinement. The procedure can be iterated. Because of eq. (8) the iteration stops when the sum of the frequency deviations of symmetrical resonators is zero. The tuning converges very fast: in general two iterations are sufficient. The detection of the mode frequencies is made by feeding a variable frequency signal in the first cell and by picking up the response in the last one. The application of SMS gives an equalization and maximisation of the field in the cavities.

We made a virtual measurement by means a program with Matlab code for 13 cavities (N=12) fed via the central one at $\pi/2$ mode (f_0=3GHz and k=4%). Eq. (5) is numerically solved with respect to the mode frequencies. We allow the cavities to be detuned by random errors with an uniform distribution in the interval (0, f). We "measure" the mode frequency shifts and the voltage at the gaps and then we adopt SMS and UPA procedures .

The results are shown in the following Fig.2 and 3.

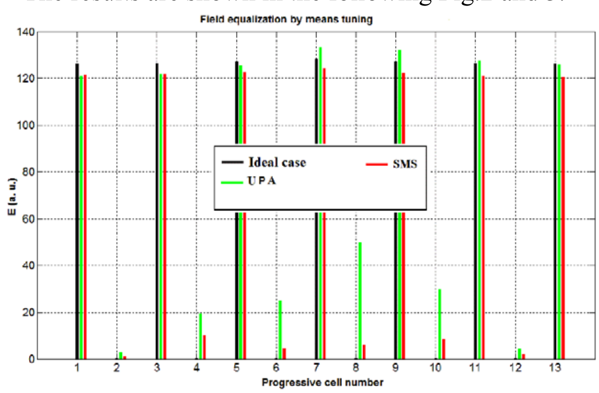

Figure 2. Comparing UPA and SMS, f= 10MHz.

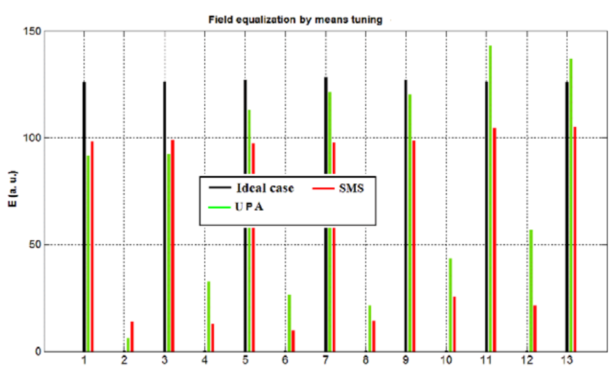

Figure 3. Comparing UPA and SMS, f= 20MHz.

From the comparison of the two techniques one has to look at the field uniformity and the power losses in CC's. From Fig. 2 and 3 we see that SMS gives a good field uniformity in any condition, better than UPA. Furthermore SMS tuning shows lower losses than UPA. The results are summarised in Tab. 1.

Table 1: Field non uniformity and power efficiency

	Field non-uniformity		Power efficiency	
	SMS	UPA	SMS	UPA
f= 10MHz	1.0%	3.4%	99.8%	96.2%
f= 20MHz	3.0%	15.9%	97.5%	92.9%

We made also a test by combining the two tuning methods. The results confirm that SMS tuning is a very good tuning method and it is the faster one: indeed the combination of SMS + UPA gives only a higher mean value of the field with the same field uniformity.

CONCLUSIONS

In this paper we showed a new tuning method. By using a circuit model it is possible to find out useful formula's to connect the mode frequency response of a coupled structure to the frequency shift of the resonators. The formula's are quite general and they show that, in order to tune the mode, the symmetrical sum of the single resonator errors must be zero. The UPA tuning technique was adopted for LIBO [7]. We have tested our method with a system of 13 cavities fed at $\pi/2$ mode. We have seen that for the cavity detuning characterised by a large spread (0.33%) a quite good field equalization and maximisation can be reached by our SMS tuning. Our method is better then UPA and it is even more, if one takes into account the losses in the coupling cavities. For even larger spreads (0.67%) a quite good field equalisation is obtained by means of SMS tuning as shown in Fig.3, while UPA produces field values with a larger spread and a significant amount of losses in the CC's. The power losses play a role in favour of SMS.

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