

# THE FIRST MODULE OF THE 3 GHz SIDE COUPLED DRIFT TUBE LINAC (SCDTL): NUMERICAL STUDIES OF RF PROPERTIES AND COLD TESTS RESULTS

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## Abstract

The 3 GHz linac section designed for the low energy (7 – 65 MeV) part of TOP (Therapy Oncological Protons) linac consists of eight modules of the structure SCDTL (Side Coupled Drift Tube Linac). The first module is designed to accelerate 7 MeV protons up to 13.4 MeV, and a prototype has been built. The non axisymmetric cavities required a full 3D modelling. Electromagnetic calculations carried out by using MAFIA code gave the the full mode spectrum. An accurate analysis of the RF properties of the structure based on an analytical model and numerical calculations was done in order to investigate in detail the first module performances and to get hints for the final design of next modules. This paper reports the results of this study and of some RF measurements on the first module.

## 1 INTRODUCTION

The TOP (Therapy Oncological Protons) linac [1,2] is designed to accelerate protons up to 200 MeV and is composed of three sections: an injector up to 7 MeV, a first 3 GHz booster up to 65 MeV and a second 3 GHz booster up to the final energy. For the medium energy section the SCDTL structure [2] has been chosen to satisfy the primary requirement of having a large shunt impedance, to get an efficient acceleration of the proton beam. It consists of short DTL tanks coupled together by a side cavity in an arrangement like a Side Coupled structure. The main differences between a standard SCL (Side Coupled Cavity Linac) and the SCDTL are that the single cavities are substituted by short Alvarez tanks, having each 5 to 7  $\beta\lambda$  long cells, and that the side cavity extends in a space left free on the axis for the accommodation of a very short (3 cm long, 2 cm o.d, 6 mm i.d.) PMQ (Permanent Magnet Quadrupole) for transverse focusing. As the neighbouring tanks operate in phase opposition, the distance between them is set equal to an odd-integer multiple of  $\beta\lambda/2$ .

The SCDTL coupled tanks are grouped in eight modules of similar length. The first module, designed for a 13.4 MeV output energy, is 1.4 m long and consists of 11 DTL tanks composed by 5 cells and 4 drift tubes equipped with two stems 180° degrees apart supporting each drift tube (Fig.1 and 2). The beam bore hole radius is 2 mm and the tank length in the module varies from 62 mm to 82.4 mm. The major part of the cavity design has

been done using a 2-D code (SUPERFISH) by which the structure geometry was optimised in order to work on the nominal frequency, maximising the operating shunt impedance and keeping the Kilpatrick value within 1.35 all through the first module.

Since the structure is not axisymmetric the MAFIA 3D code was used to investigate the characteristics of the SCDTL structures in terms of analysis in frequency both for single DTL tanks and for coupled tanks and coupling coefficient dependency on geometry. In the following the main results of the numerical calculations are discussed and some RF measurements on the first module are presented.

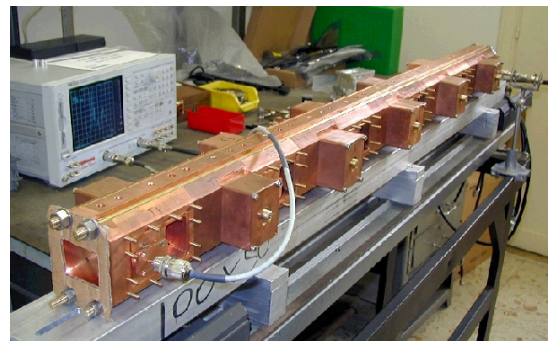


Figure 1: First SCDTL module on RF test bench

## 2 3D NUMERICAL ANALYSIS

### 2.1 Single DTL tanks

MAFIA calculations for the single closed DTL tanks show that for each tank the stem system introduces four modes associated with the transverse stem resonances (so called TS, Transverse Stem modes) producing a lower passband [3]. The remaining resonances, being higher in frequency, in part originate from the cylindrical cavity passband (fig.2), although perturbed by drift tubes and stems, and in part cannot be recognised according to the standard classification of the unloaded cylindrical cavity due to the strong coupling to the stem system. As to the transverse modes, the stems remove any degeneracy, producing couples of orthogonally polarised modes. The nearest transverse mode to the operating one are the  $TE_{111}$  with horizontal polarisation, derived from the  $TE_{111}$  unperturbed and the  $TM_{011}$  mode: in both cases the frequency results strongly dependent on the structure length and tends to approach the operating mode

frequency as the proton energy increases, because of the tank length increase.

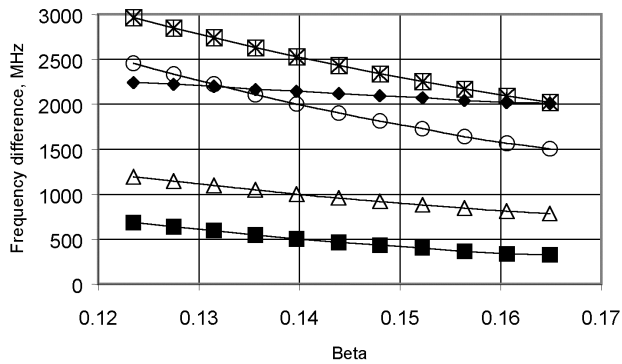


Figure 2: Higher modes in SCDTL tanks:  $\diamond$  =  $TE_{111}$ -pa;  $\Delta$  =  $TM_{011}$ ;  $O$  =  $TE_{112}$ -pe;  $\blacksquare$  =  $TE_{111}$ -pe;  $*$  =  $TM_{012}$ , where -pe stays for perpendicular, and -pa stays for parallel to stems direction.

## 2.2 Coupled DTL tanks

Figure 3 shows the first 20 modes found in the first and last triplet. The first eight modes of each triplet are the stem modes of the two accelerating tanks: they are four for the first cavity and four for the second one. After the three structure modes appear,  $0$ ,  $\pi/2$  and  $\pi$ . The two immediately following modes are  $TM_{011}$  modes of the coupling cavity. Then the  $TE_{111}$  modes of the two DTL tanks follow.

This analysis shows that the  $TE_{111}$  modes have almost the same frequency of the uncoupled DTL tanks. They are still close to the structure band, now enlarged due to the coupling, especially for the longer tanks, but, in the coupled case, the closest modes are the  $TM_{011}$  modes of the coupling cavities and, in particular in the coupling cavity number 10 (C10).

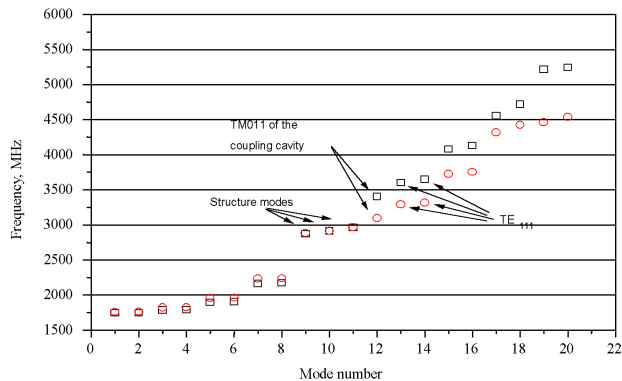


Figure 3: First 20 modes found by MAFIA in the first and last triplet; first triplet ( $\square$ ), last triplet ( $O$ ).

The field distribution of the  $TM_{011}$  mode is indeed very similar to the one that is created by the structure mode  $\pi/2$  inside C10, that is the electric longitudinal field vanishes on the axis at the cavity centre and reverses its polarity near the noses. This similarity of the pattern and the closeness of the frequencies gives the possibility of interaction of  $TM_{011}$  with the structure modes.

Simulations of all the tanks of the module grouped in triplets gave a variation of the coupling coefficients values from 3.8 to 3.3 % in a way that is about inversely proportional to the square root of the tanks volumes.

## 3 EQUIVALENT CIRCUIT MODEL

An extension to the well known equivalent circuit theory was done in order to take into account the peculiar characteristics of the SCDTL structure. The details of this study will be included in [4]. Here we will discuss the main results only qualitatively. In order to take into account the influence of the  $TM_{011}$  mode both of the tank and of the coupling cavity, given the similarity of this mode with the  $\pi$  mode of two coupled cavities, the model splits each tank in five capacitively coupled oscillating circuits corresponding to the five cells of the tank and each coupling cavity in two capacitively coupled oscillating circuits corresponding to the two cavity halves. So other two coefficients,  $k_{ct}$  and  $k_c$  are added to the usual Knapp parameters: they are the capacitive coupling coefficient of the tanks and of the coupling cavities: their values decrease with the decrease of the frequency difference between the  $TM_{011}$  mode and the fundamental mode. A MATLAB program solving the equation system representing this lumped constants model including losses and frequency errors in the single cells is in course of developing for the simulation of the whole module. At the moment the program is not complete and solves only a single quintuplet, but already some interesting properties arise. In particular for a low  $k_c$  value, the  $\pi/2$  mode frequency decreases and a distortion in the dispersion curve appears: the consequence is that the desired  $\pi/2$  mode frequency requires that the tanks frequency increases with the increase of the length. The other important influence concerns the electric field distribution uniformity which becomes more poor for low values of  $k_c$  and  $k_{ct}$ : the consequence is that also in a condition of a perfect tuning in frequency (zero field in the coupling cavities) and absence of machining errors, it is not possible to achieve a perfect uniformity in the electric field distribution. So, as we will see, in order to get the proper electric field uniformity a particular tuning technique for this type of structure is necessary.

## 4 RF MEASUREMENTS

The 11 SCDTL tanks were clamped by four rods with bolting ends placed in the cooling channels, screwing each coupling cavity to the relative tank body. The measurements were affected by the poor  $Q$  of the cavities due to the fact that the structure is not brazed. Coupled cavities contacts to the tank body have been found poor and sometimes unreliable.

Our main goal was to set a uniform average electric field  $E_0$  in all the gaps of all the tanks. However some characteristics of the structure must be considered at this

end. From tank 1 to tank 11 the length tank increases and the gap increase correspondingly but with different form factors, the tanks have all the same inner diameter and the coupling holes have the same size. This corresponds to a slightly increasing peak electric field from the tank 1 to the tank 11 averaged among the five cells in each tank. As to the tolerances, from the dynamics calculations the allowable average field inter-tank (tank to tank) error is  $\pm 3\%$  while the field intra-tank (gap to gap in the same tank) error is wider,  $\pm 5\%$ .

After the standard frequency tuning addressed to get a proper  $\pi/2$  mode and to close the stop band with zero field in the coupling cavities, the axial electric field was measured by the bead pull method using a HP8753ES Network Analyzer. However we did not reach the required field distribution. Indeed, accordingly with the lumped constants model even in the case in which no manufacture errors exist it is impossible have a perfectly flat  $E_0$  throughout the structure.

In order to set at best the field in each tank, an asymmetry of few tenths of a millimetre was set in the coupling cavities nose lengths: increasing one and reducing the other so that the frequency remains unchanged, reflects in different coupling coefficients and field levels in the neighbouring tanks. The frequency tuning of the structure is slightly affected, but can be reset by minor changes that, in turn do not affect the field distribution. This led to a field distribution within the specified tolerances in the  $\pi/2$  mode as it is shown in figures 4 and 5 where both the maximum  $E_z$  values in the gaps, and the average within the tanks among the five cells values are plotted along the structure and compared to what are the ideal fields.

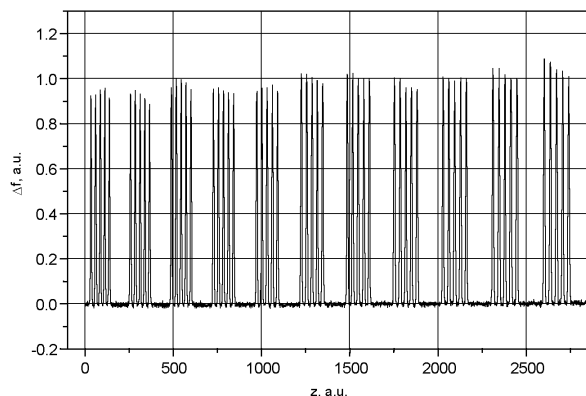


Figure 4: Measured  $E_z^2$  distribution

By shorting the neighbouring cavities (both coupling and tanks) the structure was segmented into duplets that were used to get frequencies and the 20 individual coupling coefficients (figs. 6, 7) according with a method described in [3]. The high values of the tank frequencies with respect to the  $\pi/2$  one (2994.85 MHz) was explained with the low value of the  $TM_{011}$  mode both in coupling cavities, especially at the high energy end of the module, and in the tanks. From the measured coupling coefficients

the field distribution has been computed, and it is in good agreement to the measured one.

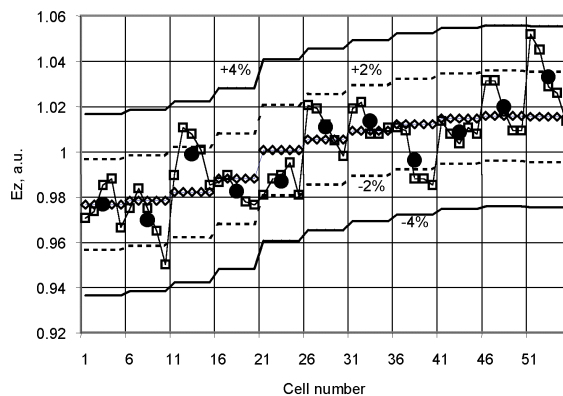


Figure 5: Peak electric fields in the cells:  $\square$  measured;  $\diamond$  = Ideal;  $\bullet$  = Tank average among the five gaps



Figure 6: Measured k values distribution

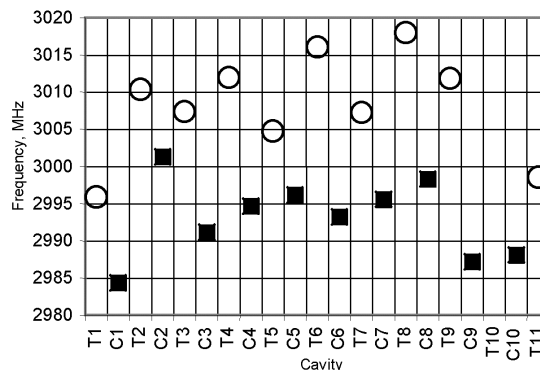


Figure 7: Measured frequency values distribution:  $\blacksquare$  = Coupling cavities  $\circ$  =DTL tanks

## REFERENCES

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