

## DESIGN, CONSTRUCTION AND LOW POWER RF TESTS OF THE FIRST MODULE OF THE ACLIP LINAC

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### Abstract

ACLIP is a 3 GHz proton SCL linac designed as a booster for a 30 MeV commercial cyclotron. The final energy is 62 MeV well suitable for the therapy of ocular tumors or for further acceleration (up to 230 MeV) by a second linac in order to treat deep-seated tumours. The possibility of using magnetrons as the source of RF power, to reduce the overall cost of the machine, is under investigation with our collaborators e2v (Chelmsford, UK). ACLIP is a 5 modules structure coupled together. The first one (able to accelerate proton from 30 to 35 MeV) has been machined and completely brazed. We plan to have the high power test by early Autumn 2008. In this paper we will review the main features of the linac and discuss the results of the RF measurements carried out on this prototype.

### INTRODUCTION

The idea of using a compact proton linac at 3 GHz for hadrontherapy, coupled with a 30 MeV cyclotron, was born at the beginning of 90s by TERA Foundation [1].

In Italy during 1999, a collaboration between TERA, INFN and CERN was born with the aim to design a 3GHz Side Coupled Linac (SCL) booster (named LIBO) for low energy protons from 62 MeV to 220 MeV. The first module of this linac, was designed, built and successfully tested boosting protons from 62 to 73 MeV [2,3].

Recently a new experiment (named ACLIP) was started for the design of a 3GHz linac able to accelerate proton beams delivered by existing cyclotrons at 30MeV [4]. The activities of nuclear medicine centres, already equipped with 30MeV cyclotrons, could be extend to proton therapy by means of this linac.

In addition, this lower energy linac could not only bridge the gap between 30MeV cyclotrons and 62MeV linac (LIBO like), but also could be used stand alone to boost the proton energy up to the values required for the treatment of non-deep tumours.

### THE ACLIP LINAC DESIGN

#### Accelerator Scheme

ACLIP was conceived as a Side Coupled Linac (SCL) working at 2998 MHz intended to increase the energy of the injected protons from 30 MeV ( $\beta = 0.25$ ) up to 62 MeV. The linac [4] consists of 5 different modules, the first of which is the object of this paper. It consists in 26 accelerating cells and 26 coupling cells, arranged in 2 tanks connected by a bridge coupler that is powered by a

single RF feed. The total length of the five modules is 3.1m. Eleven PMQs are positioned between the adjacent tanks and at the beginning and exit of ACLIP

The design value for the mean beam current, which is 8 nA, is considered to be a sufficient value for a proton therapy beam intensity.

#### Beam Dynamics

The final layout of the accelerator has been studied, starting from the scheme described above and taking the mean accelerating field as 20 MV/m. The codes used in beam dynamics computations have been Parmila and Astra. The beam has been described as a "waterbag 4D" distribution where all the particles have a uniform distribution within the phase space  $xx'-yy'$  [5].

The input data are those of 30 MeV commercial cyclotrons, namely: energy spread of  $\pm 0.3$  MeV, non normalized transverse emittance of  $40 \pi$  mm-mrad and of  $20 \pi$  mm-mrad respectively in the horizontal and vertical planes. The gradient of the quadrupoles (31 mm length, commercially available), has been optimized for a value of 190T/m.

RF power considerations led us toward a design with an aperture radius of the cells of 4 mm, which results in a non normalized acceptance of  $14.7 \pi$  mm mrad. This value, which is small in respect to the injected beam, results in the immediate consideration that a large amount of beam will be lost in the first modules. However we have performed an extensive analysis of beam dynamics up to 230 MeV and we found that it may achieve the design value of the beam current. The computed values of the optimized transmittance at different energies are shown in Table 1.

Table 1: Beam transmittances at various energies.

Energy	Transmittance
60 ± 1 MeV	8.2%
131 ± 1 MeV	7.8%
230 ± 1 MeV	7.1%

Simulations have been performed to study the possibility to vary the energy by switching off a specified number of modules and modulating the power in the last active one. Results show that the transmittance is not influenced and the energy spread is constant.

Longitudinal dynamics studies have shown that in these conditions the energy spread is smaller than 1MeV around the nominal energy at any energy value. In Table 2 we

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compare the values of the longitudinal straggling and the longitudinal dispersion due to the spread in energy.

Table 2: Range and straggling in water at various energies.

Energy	Stopping Range	Long. Straggling
60 ± 1 MeV	30.4 ± 0.9 mm	1.3 mm
131 ± 1 MeV	137.9 ± 1.7 mm	5.1 mm
230 ± 1 MeV	325.25 ± 2.4 mm	13.0 mm

*Innovative Accelerator Cells Design*

The design goal to operate at a 30 MeV injection energy or even lower forced us to deeply investigate a new accelerating SCL structure to face the problem which arises in classical SCL structures: indeed the shunt impedance drastically decreases with decreasing energies. The new design of ACLIP tiles (covered by a patent), named Back to Back Accelerating Cavity (BBAC) overcomes this problem and gives some remarkable side advantages (Patent Nr 2008 A25).

In Fig. 1 is shown one tile and a set of tiles of a standard SCL design.

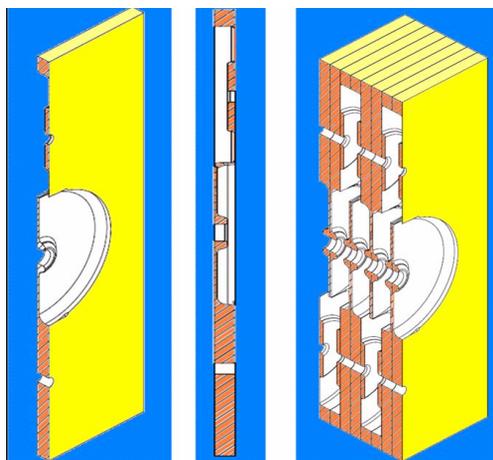


Figure 1: Standard tiles.

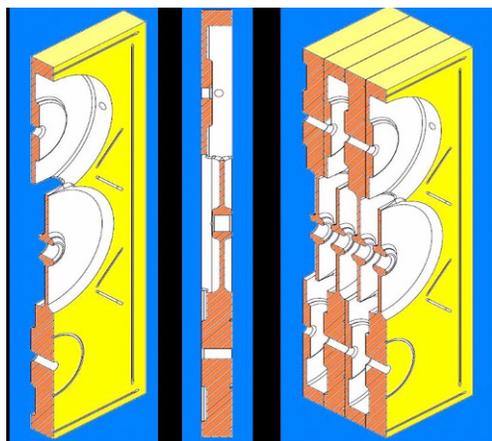


Figure 2: BBAC innovative tiles.

The innovative feature of the new design is illustrated in Fig.2, where one single and a set of BBAC are depicted.

According to the standard design (fig. 1) each tile is manufactured in order to exhibit half a coupling cavity on one face and half an accelerating cavity on the other face.

The new design (fig. 2) foresees a portion of an accelerating cavity on one face and the complementary part on the opposite one. The same applies for the coupling cavity. The cutting plane is such to divide one of the coupling slots (fig. 3). In this way the cavities are asymmetrically cut. Therefore one new tile is equivalent to two tiles of the standard design.

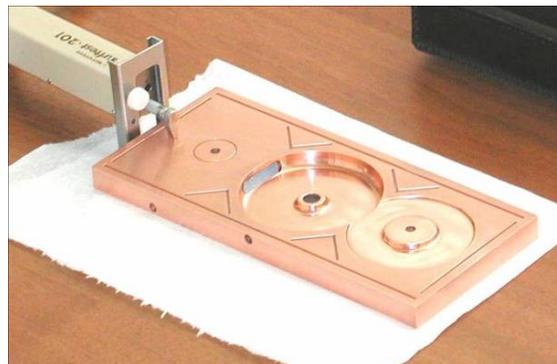


Figure 3: The innovative SCL tile.

The main advantages of this invention are:

- the septum between two adjacent cavities is no longer obtained by setting two tiles back to back, the manufacturing is simplified and the septum width can be reduced without impacting the quality of the brazing process;
- the increase of the volume surface ratio in the cavity produces an increase of the shunt impedance;
- the larger width of the accelerating cavity and its asymmetric cut allow the frequency rod tuners to be easily inserted,
- the reduced number of tiles required in the assembly provides a more relaxed mechanical tolerances and a general reduction in machining costs.

**RF ASPECTS**

*RF Design*

The RF design of ACLIP is based on the same mean accelerating field on axis in all the 10 tanks. The cavity shape has been studied by means of Superfish code at the frequency of 2998 MHz (at a working temperature of 28 °C). The design foresees a peak surface field such that the bravery factor is 1.8, with a mean axial field value of E=20MV/m. The behaviour of the coupled cavities has been studied by means of MWS Studio.

### RF Tuning

The intrinsic complexity of the basic components along with the brazing process may introduce unavoidable errors in the frequency and in the field shape. This problem has been approached from two angles. A rationale has been developed and tested to understand and to correct the behaviour of SCL structures, starting from a reduced set of measurements [6]. The tuning system, based on tuning rods, has been incorporated in the mechanical components of the modules. It may be used to compensate errors even after the final brazing. This approach allows a maximum correction factor of 6.6 MHz for each accelerating cell and 8 MHz for each coupling cell (two tuners are available).

### Low Power RF Measurements

Measurements on first module, with components simply stacked together, showed that the field was uniform to within 3% after a complete tuning procedure [7].

The brazing of the first module has been accomplished at CERN and the structure after a positive leak test was available for a complete low- level RF characterization in the first half of June 2008 (fig. 5).

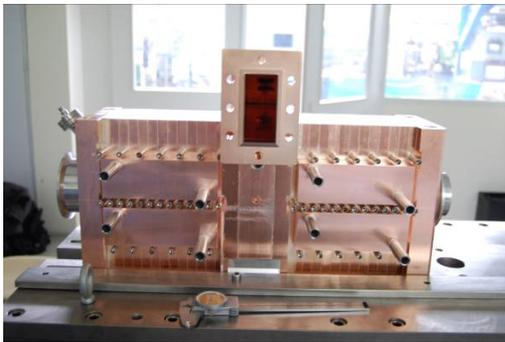


Figure 5: Assembly of the first module.

The electric field has been measured with the bead pulling technique. The measured value (fig. 6), is uniform to within 1.1%. The measurements of the quality factor  $Q$  gave a value of 6200. This is in good agreement with  $Q=6800$  obtained by simulations with MW studio, which do not consider the contribution of the brazing alloy layer.

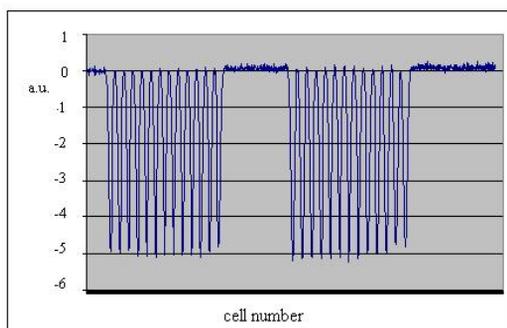


Figure 6: Field intensity vs. bead position.

### High Power Tests

An agreement has been set up with e2v (Chelmsford, UK) to carry out high power testing of the first ACLIP module with a 4 MW magnetron/modulator (MPT5839) at the Chelmsford site in the autumn of 2008.

The construction of a second module is already underway to attain a final energy, after the acceleration through the two modules, of 41 MeV. This will allow us to verify experimentally, for the first time, the possibility to use phase locked magnetrons for the powering of particle accelerator modules. RF power components used in multi-modules linac, are currently based on klystron amplifiers. Even though these components have benefited from the technological evolutions in recent years, to make them more compact and less expensive, they still remain the most costly part in the economic budget of a linac. The phase locked magnetron/modulator approach offers a possible solution.

### PRESENT SITUATION

The first ACLIP module, along with all elements of the RF power experimental setup, is ready to be transferred to e2v in Chelmsford for testing. These RF power tests are expected to take place in the autumn of 2008. On completion of the power test, the module will be moved to INFN-LNS in Catania to carry out beam acceleration tests using a 30 MeV proton beam from the Superconducting Cyclotron.

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