A SIDE COUPLED PROTON LINAC MODULE 30-35 MEV: FIRST ACCELERATION TESTS

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Abstract

ACLIP is a 3 GHz proton SCL linac designed as a booster for a 30 MeV commercial cyclotron. The whole accelerator is a 5 module structure coupled together. The final energy is 62 MeV well suitable for the therapy of ocular tumors. In order to treat deep-seated tumors the energy can be raised up to 230 MeV by adding a second linac. The possibility of using magnetrons, as the source of RF power, to reduce the overall cost of the machine, and the tile design (covered by a patent), named Back-to-Back Accelerating Cavity (BBAC), to efficiently accelerate protons starting from a low energy are two of the more relevant features of this project. The first module (from 30 to 35 MeV) has been full power RF tested in December 2008, showing that the design accelerating field could be easily reached. Then this module, along with all elements of the RF power setup, has been transferred to INFN-LNS in Catania at the end of April 2010 to carry out beam acceleration tests using a 30 MeV proton beam from the Superconducting Cyclotron. In this paper we will review the main features of the linac and discuss the results of the acceleration 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 from TERA Foundation [1] at the beginning of 90s.

In Italy during 1999, a collaboration between TERA, INFN and CERN was established 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 cyclotrons at 30MeV [4,5].

This lower energy linac could not only fill the gap between 30MeV cyclotrons and 62MeV linac (LIBO like), but it could also be used stand alone to boost the proton energy up to the values required for the treatment of non-deep tumours. In this way, the activities of nuclear medicine centres, already equipped with 30MeV cyclotrons, could be easily extended to proton therapy.

High power RF tests have been carried out on the first module of ACLIP linac showing that it can easily stand a feeding power up to 4MW (maximum peak power of the #vaccaro@na.infn.it

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magnetron), which is much larger than the design figure from of 2.8 MW [6]. This insures a comfortable security margin.

THE ACLIP LINAC DESIGN

Accelerator scheme

ACLIP was conceived as a Side Coupled Linac (SCL) working at 2998 MHz for the acceleration of protons from 30 MeV ($\beta = 0.25$) up to 62 MeV ($\beta = 0.35$). The linac [5] consists of 5 different modules, the first of which is the object of this paper. It consists of 26 accelerating cells and 26 coupling cells, arranged in 2 tanks connected through a bridge coupler and powered by a single RF feeder. The total length of the five modules is 3.1m. Eleven PMQs (gradient of 190 T/m) are positioned between the adjacent tanks and at the beginning and the exit of ACLIP.

A major feature of the ACLIP project is in the tile design (covered by the Patent Nr 2008 A25), named Back-to-Back Accelerating Cavity (BBAC).

The extraction current available from a commercial 30 MeV cyclotron may be of the order of 150 μ A. This value, with the duty cycle of 0.1% and the transmittance of a few percent characteristic of a linac, results in a mean beam current of the order of 8 nA, value which is considered a sufficient intensity for a proton beam therapy.

Beam dynamics varying the RF power

In the high power RF tests, performed at e2v in Chelmsford (UK), the magnetron test system was able to provide till 4 MW peak power. This system was no more available for acceleration measurements to be carried out at the INFN Laboratori Nazionali del Sud (LNS) in Catania (Italy).

The RF power required for the first ACLIP module is of 2.8 MW in order to reach the final design energy of 35.28 MeV.

For acceleration tests, we have used a magnetron (e2v -MG5193) with its modulator, made available by NRT (Aprilia, Italy), whose maximum deliverable peak power is 2.5 MW. In addition to this one should take into account that the reflected power cannot be compensated since we are at the threshold. As a consequence we expect an acceleration power notably lower than the nominal one.

In general for long linacs a decrease of the accelerating field may cause a partial or even total loss of beam, because the synchronous particle in order to keep pace must vary its phase to smaller values. This produces a reduction of the bucket area and a decrease of the gained energy. In the case of only one module fed at power lower than the nominal one, we expect a modest decrease of the amount of captured particles and of the maximum gained energy.

In order to study the 1st ACLIP module performance with the new feeding power condition, we made a numerical investigation on the longitudinal dynamics behaviour in a wide range of supplied power. We used the Parmila code taking a mean accelerating field of 20 MV/m, a "4D waterbag" beam distribution and 30 MeV commercial cyclotrons input data, as in all our previous dynamics computations [7].

The particle dynamics simulations have confirmed our expectations. Varying the RF power from 2MW to 2.8MW the maximum final energy changes of 2%. Furthermore, the phase angle shows a variation smaller than 1deg in the same power range.

The output beam energy distribution is shown in fig. 1 for three input feeding power values (2 MW, 2.1MW and 2.8MW).



Figure 1: Energy distribution of the extracted proton beam.

One can notice that the bucket is not yet entirely formed since its likely that the particles did not experience a complete cycle of synchrotron oscillation. However, we may assume that the bunch in formation has a peak energy of 34.2 MeV.

The acceleration detection will be a tough problem because of the presence of the long tail. Furthermore the decrease of the energy gain is not proportional to the square root of the power (namely to the accelerating electric field), because of the partial compensation of the phase angle.

ACCELERATION TESTS

On April 2010, the ACLIP module was transferred and installed at the LNS in Catania (Italy) where a proton

beam was available from the superconducting cyclotron for the acceleration tests. A view of the accelerator placed in the proton beam line is shown in fig. 2.

The proton beam delivered by the cyclotron had an energy of (30 +/- 0.1) MeV with an energy spread of the same order. The operating value of the average current at the ACLIP entrance was of the order of few nA. The beam from the cyclotron was controlled and matched to the linac acceptance by means of conventional diagnostic systems like Faraday cups and alumina screens, placed upstream and downstream of the ACLIP module.



Figure 2 : ACLIP module installed on the cyclotron beam line at LNS.

The 3 GHz RF pulse, from the feeding magnetron, had a width of 5 μ s and a repetition rate of 10 Hz. The forward maximum power was 2.5 MW with a 20% reflection; sufficient for our tests as dynamics studies have shown (see fig.1).

The cyclotron proton beam was chopped at the same magnetron repetition rate with a time window of about $30\mu s$, value necessary to compensate the time jitter in the RF pulse, but much longer than the 3 GHz linac pulse. A drawback of this choice was that a large fraction of the 30 MeV beam was transmitted through ACLIP without acceleration, rising the background level.

To measure the energy of the accelerated protons we planned to use a 25 mm thick NaI(Tl) crystal. The use of a nuclear detector was mandatory because of the very low beam intensity, the low duty cycle, and the computed overall acceleration efficiency of about 20%. The NaI(Tl) was previously calibrated using as a reference the 60 MeV cyclotron beam. The results were quite good: the energy resolution at 60 MeV was better than 1% and the linearity down to 15 MeV better than 0.5%.

The detector was placed in air directly on the beam line, and protons came out from ACLIP through a 50 micron Mylar vacuum window. The goodness of this system for measurements of energy distribution of very low intensity proton beam in this range of energy has been previously demonstrated [3]. Unfortunately, during the first RF tests, a spurious pulse, whose amplitude was of the order of ten volt, coming from the modulator (during the 5µs window) was picked up by the detector preamplifier, thus preventing us to measure any accelerated proton beam. The short time available at LNS for the tests was not sufficient to fix the problem so we decided to change the dection system and we used radiocromic films in order to try to have evidence of the acceleration.

We used an available film from Gafchromic® manufactured with two polyester sheets 100 micron thick with a 34 micron active layer in between. A stack of 6 foils was positioned at the exit window of ACLIP after a 4.2 mm thick Aluminum absorber. First of all we checked the penetration depth with the 30 MeV beam; only one foil was activated in accordance with the TRIM-code[8] calculation in the expected range.

Thereafter the RF system was turned on for about 6 hours, the whole time available for the experiment at LNS. Taking into account the pulse duration and the repetition rate, it corresponds to less than 3 sec of live time for the measurement. We point out that the total number of 30 MeV protons hitting the target are of the same order or even lower of the test without acceleration.

We found 4 foils activated, which corresponds to a maximum energy gain of 3 MeV. Taking into account that next sensitive layer is after 200 micron of polyester we can assume that the energy gain is between 3.0 and 3.5 MeV. Moreover because at higher energies the total number of protons reaching the active layer decreases drastically, it could happen that they were not sufficient to impress the active layer.

We can conclude that the value of (3.0+0.5) MeV can be assumed as a lower limit of the energy gain. The measurement represents the evidence of the acceleration, in accordance with the expectations, and underlines the goodness of all choices made in the ACLIP experiment, from the tile design to the feeding system [3,4,6,7,9,10,11].

CONCLUSIONS

The first ACLIP module has been built and successfully tested. Final tests in Catania showed that it can accelerate 30 MeV protons at least up to an energy of 33.5 MeV.

Measurements confirmed the working principle and all the mechanical choices. The construction of a second module is foreseen in order to have a better definition of the accelerated bunch and to test a new feeding system with magnetron phase-locking in beam acceleration [11].

ACKNOWLEDGEMENTS

We would like to thank e2v (Chelmsford, UK) for the essential support in the preliminary phase of this research in the high power RF tests, Acciaierie Valbruna (Vicenza, Italy) for the free supply of special Steel and AVIO Group (Pomigliano, Italy) for their support in the preliminary phase of component brazing.

We also acknowledge the valuable support received by C. Uva (INFN, Milano) and by A. Maugeri, A. Seminara, A. Santonocito (INFN LNS, Catania) during the whole ACLIP installation phase at LNS.

REFERENCES

- [1] U. Amaldi, "The Italian Hadrontherapy project", U. Amaldi and B. Larsson Eds, Elsevier, 1994.
- [2] U. Amaldi et alii "LIBO a Linac Booster for protontherapy: construction and tests of a prototype", NIM A, 2004 (vol. 512/2-3 pp. 512-529).
- [3] C. De Martinis et al, "Beam Tests on a Proton Linac Booster for Hadrontherapy", EPAC 2002, Paris, (June 2002).
- [4] V. G. Vaccaro et al., "Some Relevant Aspects in the Design and Construction of a 30-62 MeV Linac Booster for Proton Therapy", LINAC 2004, Lubeck, Germany (August 2004).
- [5] V. G. Vaccaro et al., "Study of a LINAC Booster for Proton Therapy in the 30-62 MeV energy range", EPAC 2004, Lucerne, Switzerland (July 2004).
- [6] V. G. Vaccaro et al., "RF High power tests on the first module of THE ACLIP LINAC", PAC09, Vancouver, Canada (May 2009).
- [7] V. G. Vaccaro et al., " Design, Construction and Low Power RF Tests of the First Module of the ACLIP Linac", EPAC 2008, Genova, Italy (July 2008).
- [8] J. Ziegler et al., http://www.srim.org/
- [9] V. G. Vaccaro et al., "Study of the Dynamics in a LINPAC Booster for Proton Therapy in the 30-62 MeV Energy Range", PAC05, Knoxville, USA, (May 2005)
- [10] V. G. Vaccaro et al., " A New Tuning Module for Resonant Coupling Structures", PAC05, Knoxville, USA, (May 2005)
- [11] V. G. Vaccaro et al., "A Rationale to design side coupled linac (SCL): a faster and more reliable tool", EPAC 2006, Edinburgh (June 2006)