RF HIGH POWER TESTS ON 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 one the more relevant features of this project and this investigation is carried out within the frame of a collaboration with e2v (Chelmsford, UK). ACLIP is formed by 5 modules coupled together. The first one (able to accelerate proton from 30 to 35 MeV) has been machined, completely brazed and in December 2008 full power RF tests were performed. 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 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].

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.

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 (β = 0.25) up to 62 MeV (β = 0.35). The linac [4] 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 a patent), named Back-to-Back Accelerating Cavity (BBAC).

The extraction current available from a commercial 30 MeV cyclotron may be of the order of 150 µA. 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, which is considered a sufficient intensity value for a proton therapy beam.

Beam Dynamics

The final layout of the accelerator has been studied, starting from the scheme described above and using a mean accelerating field of 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 ±0.3 MeV, non normalized transverse emittance of 40 π mm·mrad and of 20 π 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 π mm mrad. A large amount of beam will be lost in the first modules, because this value is smaller than the injected beam one. However we have performed an extensive analysis of beam dynamics up to 230 MeV and we found that the designed value of the beam current may be achieved. 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%

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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.

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 code (CST).

RF Tuning

The intrinsic complexity of the basic components along with the brazing process may introduce unavoidable errors in the working frequency and in the field shape. This problem has been faced from two sides. To properly design the SCL cavities, a rationale has been developed in order to study ex-ante the linac behaviour [6]. At the same time a new tuning system has been developed and tested to correct ex–post the behaviour of SCL structures, starting from a reduced set of measurements [7].

The tuning system, based on 110 tuning rods, has been incorporated in the mechanical components of the modules 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).

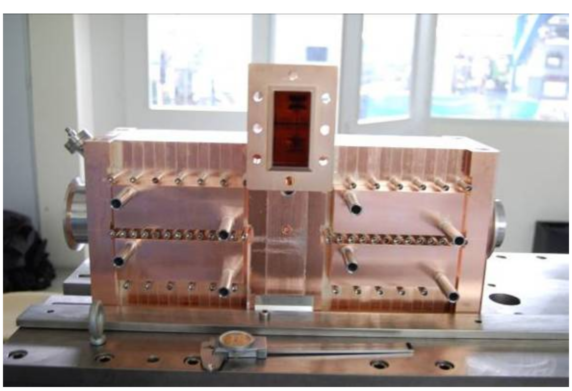

Figure 1: Assembly of the first module.

Low Power RF Measurements

Measurements on the first module, with components simply stacked together, showed that the field was uniform to within 3% after the tuning procedure [8].

The brazing of the first module was 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. 1).

The electric field was measured along the whole module with the bead pulling technique, resulting in final value, which is uniform to within 1.1% (fig. 2). The measured quality factor Q of 6200 is in good agreement with the value of 6800 obtained from simulations with MW Studio, which do not consider the contribution of the brazing alloy layer.

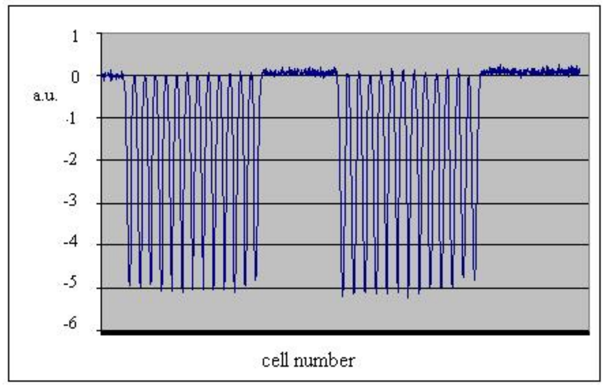

Figure 2: Field intensity vs. bead position.

High Power Tests

At the beginning of December 2008 the ACLIP module was transferred and installed at e2v in a dedicated area to carry out high power testing of the first ACLIP module with a 4 MW magnetron/modulator (MPT5839).

Figure 3: The ACLIP module high power RF test set.

Fig. 3 shows the ACLIP module installed in the high power test facility. One distinguishes the RF power feeding line coming out from the magnetron cabinet, a high power circulator (4 MW limited), a double ridge waveguide loop coupler (for high power sensing), a CML RF ceramic window, a flexible copper bellow and the coupling to the brazed input waveguide.

A 3 mm thick lead shield was put around the module to reduce the bremstrahlung X-rays emitted to an admissible level. Tubes supplying the water to the channels of the cooling plates brazed on either side of each tank are shown too. The temperature of the module is monitored by three thermocouples placed on each tank and on the bridge coupler. The chiller was able to maintain the module temperature stable within ± 0.15 °C with a cooling capacity of 2180 watts @ 20°C. This exceeds the cooling capability of the plates and tube system, which is limited to a value of 1500 watts due to space constraints.

The vacuum manifold with the ion and turbo pumps is placed beneath the ACLIP module. Vacuum levels of $2x10^{-6}$ mbar and $2x10^{-7}$ mbar were reached in the module prototype and in the vacuum manifold, respectively. The vacuum level was used during RF high power tests as one of the relevant indicators of the conditioning process, along with the measured discharge rate.

The magnetron test system was able to provide 4 MW peak power pulses at a repetition rates from 20 Hz up to 200 Hz. The pulses length may be regulated from 3 µs up to 10 µs. The requested nominal frequency of 2998.1 MHz was adjusted within the magnetron test system by a motor driven capacitor.

Stable magnetron operation below 1MW was seen as a major limitation mainly during the conditioning process. However this could be improved in the future by selection of an alternative magnetron and adjustments to the test modulator.

The high power RF testing lasted nearly 16 hours. Constrains in the time available at the test facility forced us to shorten the time for the RF conditioning.

We started the process by applying a 3 µs long pulse at 1 MW peak power, with 20 Hz repetition rate. Upon applying power to the module we observe an increase of the resonant frequency of 1.2 MHz. This shift proved to be independent of the injected peak power, pulse length and repetition rates. We ascribed this effect to a small deformation of the nose region due to the expected and unavoidable gradient of temperature between the linac body and the cavity noses themselves (nearly 10°C). The deformation influence on the frequency is remarkable.

After 8 hours the pulse length was increased up to 5.4 µs with a peak power of 4.0 MW (the reflected fraction was measured to be of the order of 10%) and a repetition rate of 20 Hz. This situation was stable with good vacuum conditions and no remarkable spark events. The same procedure was applied with the repetition rate rising up to 120 Hz. The only effect was the increase of the module temperature since the applied power load exceeded the cooling capacity of the system.

After 15 hours of conditioning we tested also a pulse length of 7 µs and a repetition rate of 20 Hz with 3 MW of peak power. The pulse shape was excellent, as shown in fig. 4.

Further increase of the RF input power was limited by the magnetron. However, there were no indications that the limit of the field level in ACLIP had been reached.

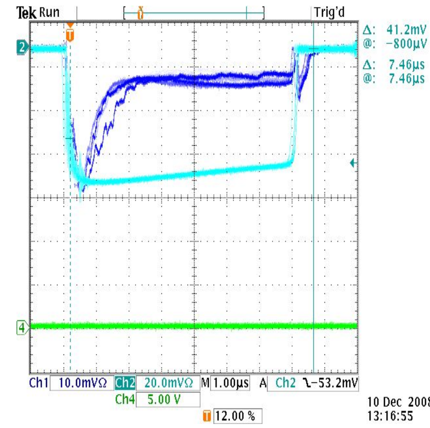

Figure 4: Forward and reflected RF pulses.

PRESENT SITUATION

The first ACLIP module, along with all elements of the RF power setup, is ready to be transferred to INFN-LNS in Catania to carry out beam acceleration tests using a 30 MeV proton beam from the Superconducting Cyclotron. These tests are expected to take place in July 2009.

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