STUDY, CONSTRUCTION AND TEST OF A 3 GHZ PROTON LINAC-BOOSTER (LIBO) FOR CANCER THERAPY

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Abstract

In a collaboration between CERN, the Universities and INFN of Milan and Naples, and the TERA Foundation, a 3 GHz, 200 MeV proton Linac-Booster (LIBO) operating from 62 to 200 MeV has been studied. LIBO is a modular structure in OFE copper consisting of nine modules, of which the first (62 to 74 MeV) is constructed as a prototype, to be tested with RF power in the year 2000. Each module is fed by a klystron and is composed of four tanks connected via bridge couplers, all brazed together. Permanent magnet quadrupoles are housed in the bridge couplers and between the modules. The design, construction and tests are described with particular emphasis on the transfer of this technology to industry.

1 INTRODUCTION

Only the essential features of LIBO are presented here. A full description can be found in references [1] and [2]. LIBO is a side-coupled proton linac intended to increase the energy of a 60-70 MeV proton beam produced by a cyclotron (already existing in several hospitals and research institutions) up to 200 MeV. This proton energy, variable between 130 and 200 MeV, is sufficient to treat deep-seated tumours. The beam optics design, with an error analysis, showed that 10% of a 62 MeV cyclotron beam operating at 25 MHz can be transmitted through the 3 GHz LIBO, provided the permanent magnet quadrupole (PMQ) alignment (the most critical error) is precise to ± 0.1 mm. Figure 1 shows the first module, out of nine, which has been constructed to serve as a prototype.

2 MECHANICAL DESIGN

2.1 Accelerator elements

All LIBO modules are essentially identical, except for their progressive increase in length, corresponding to the increasing velocity of the protons. There are three basic elements that compose the accelerating structure in each module: the “half-cell-plate”, the bridge coupler and the end cell. Each module contains 102 half-cell-plates, 3 bridge couplers and 2 end cells, see Fig. 1. The half-cell-plate is the basic building block of a tank. It is a rectangular plate containing half of an accelerating cell and, on the reverse side, half of a coupling cell, see Figs. 1 and 2. Apart from the slight difference in length, the shape of the cells

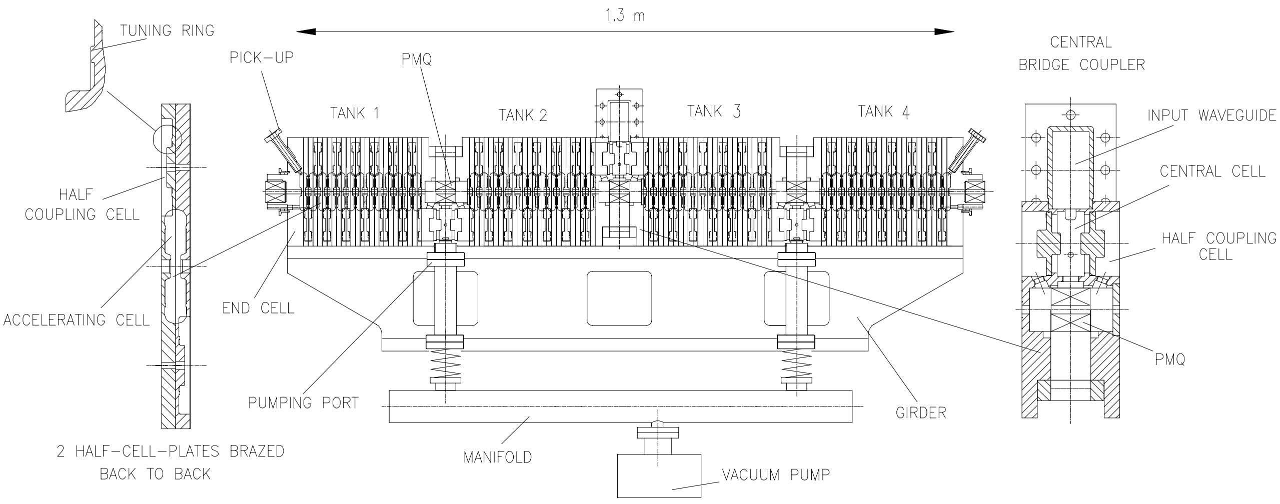

Figure 1: Layout of module 1 of LIBO with details of a half-cell-plate (left) and bridge coupler (right).

remains the same in all the modules. All accelerating cells in a tank have the same length; the length of the coupling cells as well as the shape of the coupling slots between the accelerating and coupling cells do not vary over the whole module.

Figure 2: Half-cell-plates showing a coupling half cell (left) and an accelerating half cell (right). Note the coupling slot.

The bridge couplers and end cells (see Fig. 1) have stainless steel flanges and cylindrical inserts brazed into them to fix the module on the girder, thus minimising stress and deformation in the soft copper. Connections to the beam line at both ends of the module and the pumping ports to the vacuum manifold are also in stainless steel.

In each bridge coupler and end cell are housed a PMQ for beam focussing, a pick-up loop for RF field measurements, and movable tuners for frequency corrections after the whole module has been brazed.

The finished and brazed copper structure is mounted on a rigid girder, onto which an external reference is fixed for alignment purposes.

2.2 Material, machining and brazing

All copper pieces for LIBO have been machined on numerically-controlled lathes and milling machines. The manufacturing precision of the structure must take into account RF, brazing, and alignment specifications. Typical tolerance values are ±10 to 20 μm with 0.4 μm roughness for RF surfaces and 0.8 μm for brazed surfaces.

The half-cell-plates are made of laminated OFE copper. Pre-machining, followed by a 250 °C stress relieving in air was used to obtain the 20 μm-planarity for vacuum brazing after the final machining. Bridge couplers and end cells are of forged OFE copper, while for flanges, manifolds and fixing points, forged 316 LN stainless steel is used.

For the brazing of the end cells, bridges and half-cell-plates, where the surfaces to be brazed must be horizontal, several grooves are machined in the bottom surfaces of the pieces, while the upper surfaces are perfectly flat, see Fig. 2. The positions and dimensions of these grooves, determining the quantity of the brazing alloy, have been tested on sample pieces with an automatic total-immersion ultrasonic testing method.

All of the half-cell-plates are machined with the external surfaces as reference, and then these surfaces are used for the alignment during the brazing of a tank. These surfaces are machined with sharp angles in order to avoid any flow of the brazing alloy into the RF cavities. The complete module is obtained by the brazing of 17 sub-assemblies, already individually brazed at higher temperature. For the different brazing steps, commercially available silver-base alloys are used, with decreasing brazing temperatures ranging from 850 °C to 750 °C. All brazing operations are performed in all-metal vacuum furnaces.

2.3 Cooling

The cooling of the LIBO module is provided by water flowing through channels inside specially designed copper plates. Two of these are brazed to either side of each tank, giving eight parallel circuits per module with a total water flow of 200 l/min. A transfer forced convection coefficient of 14000 W/(m^2 °C) for each circuit assures the cooling of the LIBO tank at full power of 2.3 kW (corresponding to a repetition rate of 400 Hz and an RF pulse length of 5 μs).

The results of a 3-D finite elements code simulation with lateral cooling can be summarised as follows:

- The maximum temperature gradient between the nose of the accelerating cell and the lateral sides of the tank is just below 7 °C.
- Thermal expansion of the nose region is about 10 μm and the frequency change due to temperature (detuning sensitivity) is about 60 kHz/°C.

Frequency tuning during operation will be done by regulating the water flow in each tank.

3 RF ASPECTS

3.1 Tuning during production

The tuning of the small LIBO cells is done in parallel with the production, in a series of steps. Each half cell in the tank has a 0.7mm high and 2mm wide tuning ring on the flat face, see Fig. 1. Remachining this ring brings the individual half cell frequency inside ±0.5 MHz of the nominal value with conventional machining tolerances. The sensitivity of the frequency to the machining is about 1.5 MHz per 0.1 mm of the ring height.

To compensate for residual frequency errors due to the brazing of the cells and to tune the complete module to the correct operational frequency, each half cell has a lateral hole where a small tuning rod is inserted, adjusted to the correct length, and then brazed at the last brazing step. With the experience gained from the prototype, rod tuning will be replaced by the “dinging” technique in future modules.

3.2 RF design

The design of LIBO is based on the same mean accelerating field on axis in all the tanks. To achieve this in the prototype, the accelerating cells are increased in length from tank to tank (conforming to the increasing velocity of protons), while the coupling cells and the coupling slots in all of the half-cell-plates (coupling coefficient ~ 4%) of the module remain the same.

The bridge couplers between the tanks are of the 3-cell magnetically coupled type. The two coupling cells in the bridge coupler are longer than in the tanks, to provide sufficient space to house the PMQ, see Fig. 1. The “accelerating” cell of the central bridge coupler has an iris to connect it to the waveguide, which brings the RF power to the module. The waveguide is tangent to the central cell, see Fig. 1, and is terminated by a short-circuit at $\lambda/4$ from the iris.

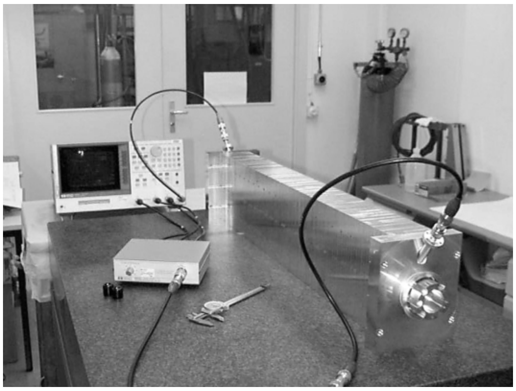

Figure 3: Measurement set up

3.3 RF measurements

The main problems in the RF measurements of cells before brazing stems from low Q-values due to ill-defined RF contacts over the large surface between half cells. Special tools have been designed and built to improve the situation and typical Q-values of about 2000 have been obtained with single half-cell measurements. The Q-value of an unbrazed tank was only 700 (instead of the nominal 7500), being one of the main reasons for the frequency changes after the brazing.

After the brazing of all individual tanks of the prototype (tank 1 and 4 with end cells), they have been aligned on a marble table for RF measurements, see Fig. 3. Without inserting any rod tuner, a field flatness of ±3.5% has been obtained. A preliminary insertion of rods brought this value to below ±2%. The bridge couplers will be inserted in the assembly after the first tuning and field adjustment of the tanks. The final trimming of the frequency and the fields (elimination of any residual asymmetries between the tanks) will be made by movable piston tuners available in each bridge coupler cell and end cell. These adjustments have to be made before putting the structure under vacuum.

4 TESTS AND CONCLUSION

The prototype of LIBO, the module 1, is to be installed in the LIL area at CERN in September 2000 to undergo full RF power tests, using the existing spare 3 GHz facility. The RF tests will be completed by the end of the year, and thereafter the module will be transported to the INFN Laboratori Nazionali del Sud in Catania, and installed downstream of the existing superconducting cyclotron for tests with a proton beam [3].

The 3 GHz klystron and modulator facility for the tests in Catania will be made available by Scanditronix-IBA, in the frame of an agreement reached with the LIBO collaboration. If these tests are successful, the way to a true technology transfer of the accumulated know-how to a consortium of companies will be open. There is a concrete possibility to bring LIBO to the medical market, because very advanced facilities for deep protontherapy can be obtained by adding it to existing 60 to 70 MeV cyclotrons.

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