BEAM TESTS ON A PROTON LINAC BOOSTER FOR HADRONTHERAPY

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Abstract

LIBO is a 3 GHz modular side-coupled proton linac booster designed to deliver beam energies up to 200 MeV, as required for the therapy of deep seated tumours. The injected beam of 50 to 70 MeV is produced by a cyclotron like those in several hospitals and research institutes. A full-scale prototype of the first module with an input/output energy of 62/74 MeV, respectively, was designed and built in 1999 and 2000. Full power RF tests were carried out successfully at CERN using a test facility at LIL at the end of the year 2000. In order to prove the feasibility of the acceleration process, an experimental setup with this module was installed at the INFN Laboratorio Nazionale del Sud (LNS) in Catania during 2001. The Superconducting Cyclotron provided the 62 MeV test beam. A compact solid-state RF modulator with a 4 MW klystron, made available by IBA-Scanditronix, was put into operation to power the linac. In this paper the main features of the accelerator are reviewed and the experimental results obtained during the first beam acceleration tests are presented.

1. INTRODUCTION

The purpose of the LIBO project is to build a modular linear accelerator to be used in cancer treatment. Coupled to a 50-70 MeV proton cyclotron, such as those used in certain hospitals for ocular cancer therapy, the LIBO will boost the beam energy in order to treat deep-seated tumours. The aim is to achieve energies of between 130 and 200 MeV, gradually adjustable, thereby allowing tumours as deep as 25 cm to be reached with great precision [1].

To investigate the feasibility of such a project, a prototype module was built at CERN by a collaboration set up in 1998 between CERN, the TERA Foundation, the Universities of Milan and Naples and their INFN sections.

In the summer of 2001 the module was installed at LNS where it passed its first acceleration test. It is the first time that such a low energy proton beam (62 MeV) is accelerated at such a high frequency.

2. LIBO DESIGN

2.1 Accelerator structure

LIBO is a side-coupled linac (SCL) operating at 2998 MHz. The project foresees a structure composed of nine basic units, called modules, each one fed by its own RF chain. All LIBO modules are essentially identical, except for their gradual increase in length, corresponding to the increasing velocity of the protons. Each module has 52 accelerating cells and is composed of four tanks, resonantly coupled via three bridge-couplers. The central bridge-coupler is connected to the RF feeder line and the others to the vacuum system. In each bridge-coupler as well as in the two end cells of the module, a permanent magnet quadrupole (PMQ) is housed to form a FODO focusing lattice.

The mechanical structure was designed using as the basic building block a rectangular plate of laminated OFE copper containing on one side half an accelerating and, at the other, half a coupling cell. Apart from the slight difference in length, the cell shape remains essentially the same in all the modules. The bridge couplers and end cells are of forged OFE copper, with brazed 316 LN stainless steel flanges for vacuum openings, RF pick-ups and fixation slugs.

The components so far described are joined to form the vacuum tight structure of a module by means of a multi-step brazing process. Brazing was performed at four temperature levels ranging between 750° and 850° C in an all-metal vacuum furnace. The copper structure is fixed on a precisely machined steel girder to insure the necessary rigidity.

The cooling of each module was designed as a separate subassembly composed of channels machined inside dedicated copper plates. These plates are then brazed on the two lateral sides of each tank. No cooling channels exist inside the accelerating copper structure, which is kept at resonance by controlling the cooling water temperature. Such a choice simplifies the whole mechanical structure and improves its reliability.

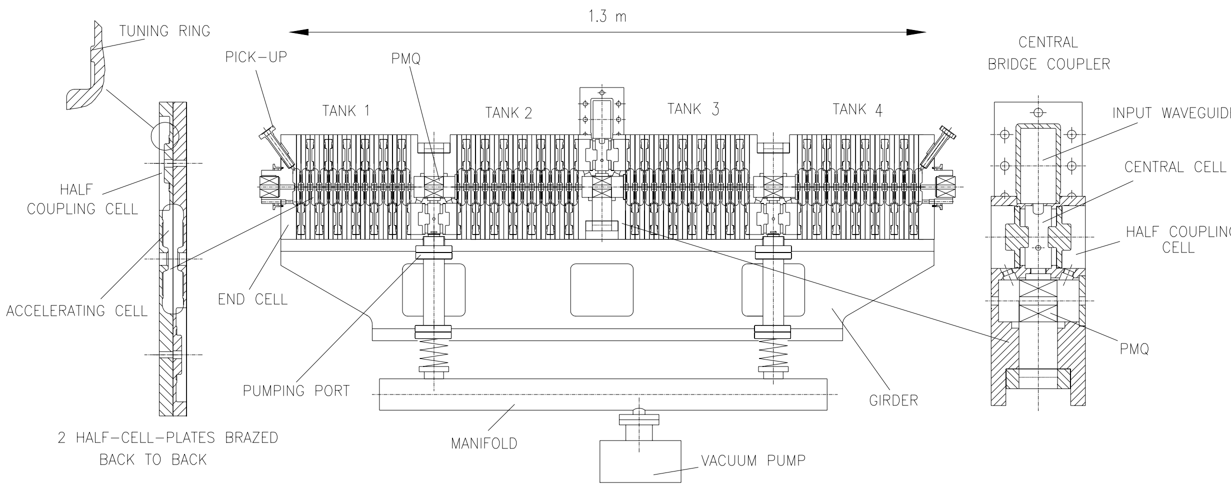

Figure 1: Layout of LIBO module prototype with details of a half-cell-plate (left) and a bridge coupler (right).

2.2 RF design

The basic choice in the LIBO design was to have an equal average accelerating field in all the tanks of a module. To achieve this, the accelerating cells are increased in length from tank to tank (conform to the increasing velocity of protons), whereas the coupling cells and the coupling slots in all the half-cell-plates (coupling coefficient ~ 4.5%) of the module remain the same.

The bridge couplers between the tanks are of the 3-cell magnetically coupled type. The waveguide of the RF feeder line has been brazed tangentially to the central bridge coupler and terminated in a short-circuit at 5λ /4 from the centre of the coupling iris.

The frequency adjustment procedure was based on the use of tuning tools during the different steps of the machining and brazing process. Tuning rings were used during lathe and milling machining. Tuning rods of the proper length were brazed in the accelerating and coupling cells. Tuning screws were used in the bridge couplers and end cells.

The accelerating field distribution in the four tanks of the first prototype of LIBO was measured to be uniform within $\pm$ 3%.

3. FIRST HIGH POWER TEST

The LIBO module prototype was installed in a test area at LIL, CERN, in November 2000 [2] to take advantage of a 35 MW klystron/modulator test system available along with vacuum equipment and a thermostat-controlled water supply.

The nominal accelerating filed level of 15.7 MV/m was achieved in a relatively short time (72 hours) without multipactoring and with a very limited number of breakdowns. A field level of 27.5 MV/m was reached after 14 hours of additional conditioning.

4. ACCELERATION TESTS IN CATANIA

In July 2001 the LIBO module was transported to and installed at the LNS in Catania. A view of the accelerator placed in the proton beam line is shown in fig. 2.

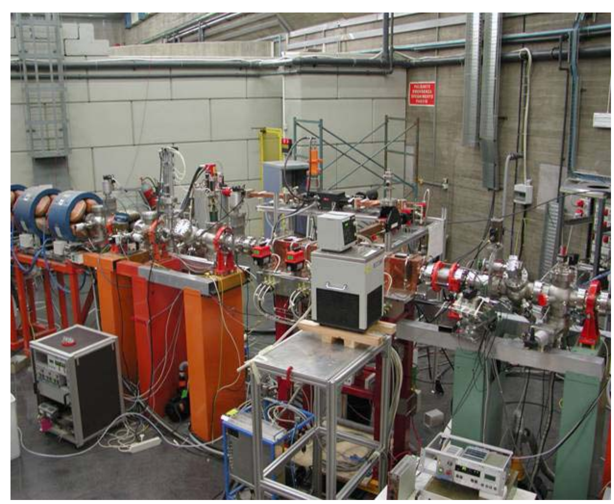

Figure 2: LIBO installed in the test beam line at LNS

A set of three quadrupoles upstream of LIBO served to match the LNS Superconducting Cyclotron proton beam to the linac acceptance, which was calculated as being of the order of 12 π mm mrad (unnormalised). The proton beam delivered by the cyclotron had an energy of 62 ± 0.2 MeV and the operating value of the average current at the LIBO entrance was of the order of 1 nA.

Conventional diagnostic systems like Faraday cups and alumina screens were placed upstream and downstream of LIBO. Moreover, a set of movable thin scintillating fibers developed at LNS [3] was used to control the beam profiles. This system was extremely useful for centering the beam at very low intensities (fraction of pA).

At the end of 2001 a very compact solid-state modulator and a 3 GHz klystron, lent under a collaboration with the firm IBA/Scanditronix, was installed and coupled to LIBO. First acceleration tests were performed during February and May of this year. The 3 GHz RF pulse had a width of 5 μs and a repetition rate of 10 Hz. The incoming proton beam was chopped in the injection line of the cyclotron, at the same repetition rate, and with a time window of about 30 μs. This value was much longer than the 3 GHz pulse, but it was necessary to compensate for the time jitter in the chopper. A drawback was that a large fraction of the 62 MeV was transmitted through LIBO without acceleration. To measure the energy of the accelerated protons, a 25 mm thick NaI(Tl) crystal was used. 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 calibrated in energy resolution and linearity using as a reference the 62 MeV cyclotron beam. The results were quite good: the energy resolution at 62 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 LIBO through a 50 μm mylar vacuum window. Measurements of the LIBO output beam were strongly affected by the very intense component at 62 MeV. To avoid this effect, a 30 mm thick Perspex absorber was placed in front of the detector. The 62 MeV component was then completely stopped in the Perspex, and only protons with an energy above 65 MeV could reach the detector.

A typical spectrum of the accelerated proton beam is shown in fig. 4,.where the energy of the protons is corrected for the absorptions in the beam path (Mylar windows, Perspex absorber, air and detector entrance windows).

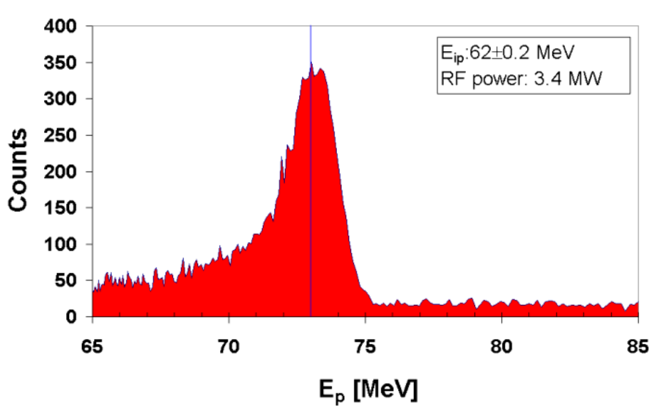

Figure 4: Energy spectrum obtained downstream of the LIBO module.

The peak energy of 73 MeV, corresponding to an energy gain of nearly 11 MeV, was obtained by injecting only 3.4 MW of RF power into the cavity (due to limitations in the driver amplifier), while the nominal value is 4.3 MW. Further measurements using a deflecting magnet in order to separate the different energy components, confirmed the above results. Moreover, the computer simulations of a 62 MeV beam accelerated in the LIBO module with 3.4 MW of peak RF power and transmitted trough the different absorbers are in very good agreement with the measured values.

5. CONCLUSIONS

The prototype module of LIBO has been successfully tested at LNS accelerating the 62 MeV proton beam to an energy of 73 MeV, well in agreement with the results of the simulations. The working principle of LIBO has been completely demonstrated. Tests of the accelerated beam will be completed next July, measuring the acceleration efficiency of the structure. As of now, only a rough estimate of the lower limit of this value exists, being of the order of 10%.

6. ACKNOWLEDGEMENTS

The tests in Catania and their success would not have been possible without the invaluable help received from many people. At the PS division of CERN, the RF, PO, PC and PP groups lent us several pieces of equipment, while the vacuum group of LHC supplied the required pumps. The installation and acceleration tests at the LNS-INFN had the support of the people of the Catania laboratory. Luciano Grilli, from the University of Milan, has given a continuous and decisive help since the beginning of the preparation for the tests. To all of these people go our deepest thanks.

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