LIBO — A 3 GHZ PROTON LINAC BOOSTER OF 200 MeV FOR CANCER TREATMENT

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Abstract

Several hospitals and laboratories possess proton cyclotrons with output energies of 60 to 70 MeV. A high frequency (3 GHz) booster linac (LIBO) is proposed to upgrade the cyclotron beam to an energy of 200 MeV, sufficient to treat deep seated tumours. LIBO is a side-coupled linac which can produce beams with a variable output energy. This paper presents the feasibility study of such an accelerator, together with the milestones planned for 1998-1999, including the machining of a part of LIBO and testing it with full RF power on a test stand at CERN.

1 INTRODUCTION

The design of a novel high-frequency proton linear accelerator of 200 MeV for medical purposes was proposed by the TERA Foundation in 1996 [1]. Such an accelerator has been further studied at ENEA, Frascati, Italy, and the low energy part of it is now under construction [2]. Reference [1] briefly describes a study of a booster linac, LIBO, intended to upgrade a cyclotron beam energy from about 60 MeV (already available in several hospitals and research institutions) to 200 MeV in order to treat deep seated tumours. In an earlier proposal [3] a similar but lower frequency upgrade was considered for the 62 MeV cyclotron of the Clatterbridge Centre for Oncology, UK. LIBO studies are also based on the Clatterbridge cyclotron, but the operating frequency has been pushed into the S-band in order to reduce the accelerator size and increase its breakdown limit.

LIBO is a side-coupled linac (SCL) operating at 2998 MHz. It is composed of 36 tanks, separated by permanent magnetic quadrupoles (PMQs). Four tanks are grouped into a module, an RF unit, fed by its own RF chain.

The average output beam required from LIBO is of the order of 10nA, and it must be possible to vary its energy from about 130 to 200 MeV. This constrains both the number of tanks in a module and their length.

The 3 GHz klystrons used to power the tanks operate in the pulsed mode with pulse lengths of up to 5 μs, but it is the average power a klystron can deliver that limits the LIBO duty cycle. The energy spread in the LIBO beam should be narrow enough to limit the distal fall off of the dose given to the patients to ≤ 2 mm. A beam pulse repetition rate of 400 Hz has been chosen to suit an active beam scanning method (e.g. pixel scanning). Preliminary tests have been performed to pulse the Clatterbridge cyclotron beam [4] to study its use as a LIBO injector

2 BEAM OPTICS

Beam optics studies have been made in order to find a suitable layout of LIBO. A high average axial accelerating gradient E_0 (15.3 MV/m) has been selected to limit the accelerator length and care has been taken to avoid synchro-betatron parametric resonances. The cyclotron beam will be matched transversely to LIBO by focusing elements placed between the two accelerators and the aperture radius of 4 mm will make the transverse acceptance A_t such as to contain the cyclotron beam emittance ($A_t \cong 12\ \pi$ mm mrad).

Longitudinally the situation is different. Only part of the low frequency cyclotron beam falls into the short LIBO buckets and many particles remain outside. This effect has been analysed by simulating the cyclotron beam, which appears continuous in phase when referred to the LIBO frequency of 2998 MHz, and dividing it into many thin phase slices which span 360 degrees. Each slice is followed through the linac with a beam dynamics program, and LIBO is optimised in a preliminary way, assuming no misalignments. It is then found that about 50% of the continuous beam can be transmitted and about 25% of the transmitted beam is fully accelerated. Thus the accelerated beam is about 12.5% of the input beam. Most of the rest of the beam leaves with energies below 70 MeV.

Misalignments of PMQs and linac tanks, and other errors, such as quadrupole gradient errors, can reduce the intensity of the accelerated beam. One can estimate the effect of quadrupole misalignments on the transmission by making a Monte Carlo optics calculation.

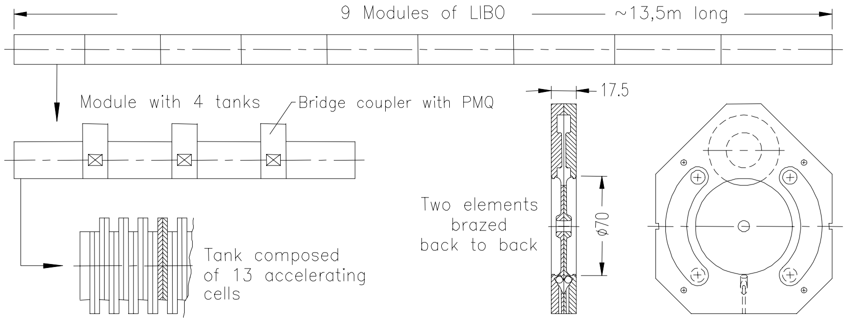

Figure 1: Schematic layout of LIBO

Four types of error have been analysed: quadrupole displacement errors of ±0.1 mm; tank displacement errors of ±0.1 mm; quadrupole rotation errors of ±1°; and quadrupole strength errors of ±1%. The only error that produces any significant reduction in the transmission is quadrupole displacement. For a displacement error tolerance of 0.1 mm there is a 90% probability that the transmission will be greater than 10%, and about a 50% probability that the transmission will be greater than 11%. With a 10% transmission and a beam duty cycle of 0.0018 (400 Hz and 4.5 μs) the LIBO trapping efficiency will be 1.8×10^{-4} and hence, in order to have an average output current of 10 nA, the peak intensity in the cyclotron beam pulse should be about 55 μA.

3 LIBO STRUCTURE

A schematic layout of LIBO is shown in Figure 1. Nine modules, each comprising four tanks, are mechanically coupled together to form the 13.5 m long accelerator. A tank has 13 accelerating cells, which are formed from 24 basic elements and from 2 half end cells. Each basic element consists of half of an accelerating cell and half of a coupling cell. The tanks of a module are resonantly coupled together via three bridge couplers. The central coupler is connected to the RF feeder line and the remaining two to a vacuum system. An RF pick-up is installed at either end of each tank and PMQs, placed between the tanks, form a FODO focusing lattice. The soft copper linac will be precisely aligned by fixing it on a rigid support with pre-adjusted keys.

The shape of the cells has been studied using the program SUPERFISH. Investigations have included, among other things, the effect of the accelerating cell diameter D and of the web thickness w (wall between two accelerating cells) on the effective shunt impedance ZT^2 and peak surface field E_{peak}. The shunt impedance includes the effect of slots for 3% coupling. The upper curve in Figure 2 shows that at the high energy end of LIBO (β=0.56), the chosen diameter D of 70 mm is optimum with respect to ZT^2. The lower curve shows that at the low energy end (β=0.35) there is little to be gained in ZT^2 by reducing D and that E_{peak} would increase rapidly. With D=70 mm, E_{peak} is limited to a conservative value of 1.6 times the Kilpatrick limit E_{k}.

Figure 3 shows that a thin web thickness w is preferable, as one might expect from the short cell lengths of LIBO. A 4 mm web has been chosen for a good mechanical rigidity of the pieces during machining and it has been decided to braze two basic elements back to back before the final machining of the accelerating cells. However, the really delicate issue is whether cooling channels are required in the web or whether circumferential cooling alone is sufficient. Cooling channels would necessitate a relatively thick web, which spoils the electrical characteristics and complicates the mechanical design, adding an extra risk and cost.

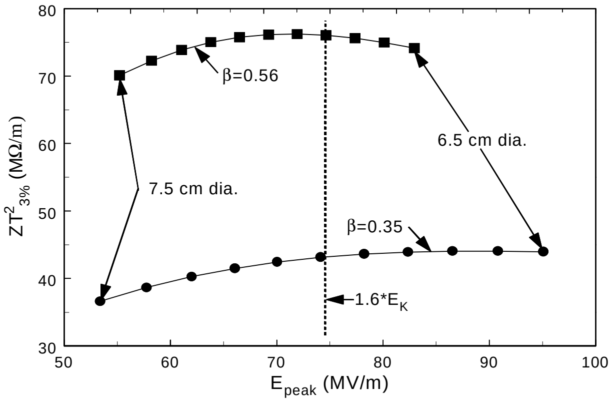

Figure 2: The points show the shunt impedances and the peak surface fields for 11 different cell diameters D, at the input (β=0.35) and output (β=0.56) energy. The web thickness w is 4 mm.

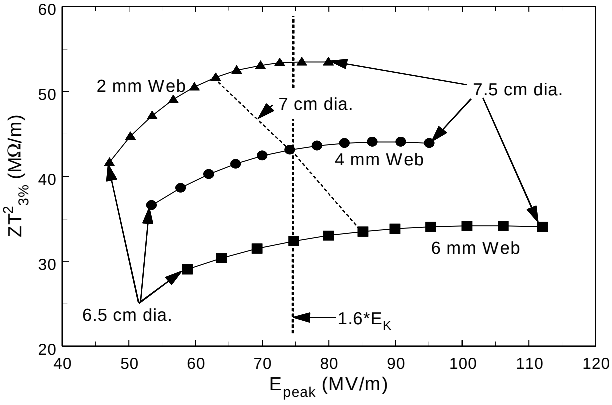

Figure 3: The points show the shunt impedances and the peak surface fields for 11 different cell diameters D and for 3 web thicknesses w, at the input energy (β=0.35).

The cooling problem has been studied assuming an RF duty factor of 0.2%, for which 150 W are dissipated in each accelerating cell of tank 1. Very little power is dissipated in the coupling cells because LIBO operates in the $\pi/2$ mode. The study has proceeded as follows:

- A table of surface coordinates of an accelerating cell and of the power density distribution on its walls is generated by SUPERFISH.
- The table is read by a finite element engineering code ANSYS, together with the specifications of the cell material. In our model this material extends to a radius of 40 mm, where a thermal boundary is defined. Simple cooling is simulated by fixing the sink temperature, T_{sink}, at this radius, where one may reasonably expect the temperature to be uniform. ANSYS computes the temperature distribution, the thermal stresses and the mechanical deformations of the cell. In our case, there was a temperature gradient between the nose (centre of the cell) and T_{sink} of about 7° C.
- A special code has been written to compute the frequency of distorted cells. The code reads the coordinates of the deformed cell surface from ANSYS, compares them with the original ones and computes the frequency detuning Δf by using Slater's perturbation theorem. The detuning is found to be about –250 kHz if T_{sink} is held at its ambient value.
- By lowering T_{sink}, the original cavity can be mechanically deformed in the opposite sense. Using ANSIS and the special code, it was found that changing T_{sink} by –5° C brings the cell back on tune; see Figure 4.

The conclusion is that circumferential cooling will be adequate for LIBO and that by controlling T_{sink} with the frequency feedback loop, it will be possible to keep the accelerator on tune.

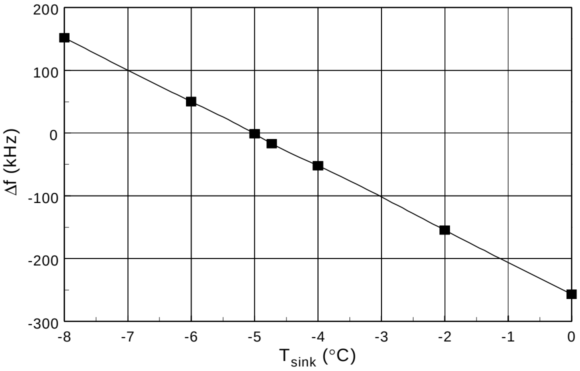

Figure 4: Detuning Δf as function of the lowering of the sink temperature T_{sink}.

The effects of coupling slots between cells have been studied with the 3-D program MAFIA. The PSPICE program, dealing with coupled circuits, has been used to assess the importance of various errors in the presence of incompletely closed stop bands. Cold RF measurements on a few cells of an aluminium model at CERN completed the studies of LIBO.

4 FEASIBILITY TEST

The SCL type of structure is usually used with lower frequencies or with higher β values than those foreseen for LIBO. It is therefore important to carry out a feasibility test prior to the construction of a complete medical booster linac. In a collaboration with High Vacuum Process (HVP), Parma, Italy, the following milestones have been set:

- Construction of a model of the first LIBO tank in copper (at HVP) in order to master the delicate parts of the production (machining, tuning, assembling, brazing, cooling etc). It should be completed in the second half of 1998.
- Construction of the complete first LIBO module (at HVP) to be tested with full RF power at CERN; the module will be pumped, water cooled and powered by a spare 3 GHz chain of LIL, and it will also contain pick-ups for RF feedback. The tests at CERN are planned for the end of 1999.

5 ACKNOWLEDGMENTS

Our CERN collegues, L. Bassi, P. Bourquin, A. Millich and R. Zennaro participated in several studies presented in this paper; A. Catinaccio, in particular, dealt with the deformations of the structure and the resulting detuning. J. Lipp of RAL assisted in this analysis. K. Hübner, D. Simon and the PS division of CERN supported this project in many ways and rendered, together with S. Ferrari (HVP), the fixing of our milestones possible. To all of them go our deepest thanks.

The financial support of the Price Foundation is gratefully acknowledged.

6 REFERENCES

[1] U. Amaldi, M. Grandolfo and L. Picardi, editors, "The RITA Network and the Design of Compact Proton Accelerators", INFN, Frascati 1996, ISBN 88-86409-08-7.

[2] L. Picardi, C. Ronsivalle and A. Vignati,"Progetto del TOP Linac", RT/INN/97/17, ENEA, Frascati 1997.

[3] M. P. S. Nightingale, A. J. T. Holmes and N. Griffiths, "Booster Linear Accelerator for Proton Therapy", Proceedings of the Linear Accelerator Conference, Ottawa, Canada, August 24-28, 1992, 398-401.

[4] J. A. Clarke, D. M. Dykes, C. W. Horrabin, H. L. Owen, M. W. Poole, S. L. Smith and V. P. Suller, "Assessing the Suitability of a Medical Cyclotron as an Injector for an Energy Upgrade", Proceedings of the EPAC – 98, Stockholm, Sweden, 1998.