Conception, construction et essai
d’un accélérateur linéaire à protons impulsé
à 3 GHz (LIBO) pour la
thérapie du cancer

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1. Introduction
LIBO concepts

• A new compact LINac BOoster for hadrontherapy


• LIBO boosts the energy of proton beams extracted from a cyclotron up to 200 MeV for deep-seated tumours
In 1998 an international collaboration, chaired by Dr Mario Weiss, has been established for the design, construction and test of the first prototype module of LIBO-62 facility.

- TERA Foundation
- CERN
- University and INFN of Milan
- University and INFN of Naples
Libo Collaboration 1998-2002

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\textsuperscript{(4)} INFN and Milan University
\textsuperscript{(5)} INFN and Naples University
Main Milestones for the LIBO prototype:

- Design

- Construction at CERN in the frame of the Technology Transfer Division (Dr H. F. Hoffmann)

- High power RF tests at CERN and beam tests at INFN-Laboratorio Nazionale del Sud, Catania, Italy
2. Brief description of a LIBO facility
Main features of LIBO

- Compact modular linear accelerator (SCL type)

- Conceived in view of the Technology Transfer to industry for medical applications
What is a compact accelerator for protontherapy?

U. Amaldi → Hadrontherapy program
→ PACO project (COmpact Accelerators Project for protontherapy), 1993.

- Acceleration of $2 \times 10^{10}$ p/sec (min.) to an energy of at least 200 MeV (running efficiency comparable with the conventional electron linacs);
- Installation of the facilities in a bunker with a total area of 300 m$^2$ or less;
- Maximum power consumption of 250 kW;
- A 60 MeV beam for eye melanoma therapy at low cost;
- Typical beam characteristics required for protontherapy
Compact modular linear accelerator (SCL type)

- A Side Coupled linac (SCL) is a biperiodic RF structure operating with $\pi/2$ normal mode.
- This structure shows good stability and high efficiency.
- Experience from Los Alamos National Laboratory: structures operating at 800 MHz and designed for protons with $\beta > 0.4$. 

![Diagram of Compact Modular Linear Accelerator (SCL type)](image-url)
Compact modular linear accelerator (SCL type)

LIBO is a Side Coupled Linac structure (SCL) operating at 3 GHz in order to reduce the size of the full accelerator for medical applications and with $0.35 < \beta < 0.56$. 

Conceived in view of the Technology Transfer to industry for medical applications

LIBO module is a mechanical entity where all the parts have been machined on standard numerically controlled (CNC) milling machines or lathes, checked by RF measurements, metrology, and brazed together with standard industrial processes.
Clinical beam parameters for protontherapy

- Minimum and maximum depth: 2 g/cm² - 20 g/cm²
- Range variation accuracy: 0.05 cm
- Distal dose fall off at any energy: 2 mm (80% - 20%)
- Dose rate:
  - 45 Gy/min for eye melanoma treatment
  - 2 Gy/min for deep seated tumours
  - (field size 20 x 20 cm²)

Nominal physical beam parameters of LIBO

- Energy: 30 - 200 MeV and continuous energy variation between 130 and 200 MeV
- Energy spread: < 0.75% above 100 MeV, < 0.23% at 65 MeV
- Beam intensity: 0.1 - 10 nA
- Beam time structure: pulse duration 5 μsec, repetition rate 400 Hz

It fits the active scanning application
How LIBO works

• Total efficiency cyclotron-linac: order of $10^{-4}$ (trapped beam $\sim 10\%$, duty factor 0.2%)

• Input current from the cyclotron: 50 $\mu$A

\[
\rightarrow \text{Output current from LIBO: } 5 \text{ nA } \rightarrow \text{ enough for cancer therapy}
\]
Beam time structure:

- Repetition rate 400 Hz
- Macropulse length 5 μsec

The micropulses or bunches are spaced at the RF period of 0.33 nsec. At the injection the buckets are open and the particles are trapped in the stable regions.
LIBO-62: basic description

- It is a Side Coupled RF structure where the oscillating electromagnetic field is used to accelerate protons
- It is composed by nine modules, each divided in 4 accelerating tanks and three bridge couplers
- Each module is a RF unit powered by a 3 GHz klystron
- Input energy 62 MeV
- Output energy can be varied between 130 and 200 MeV
<table>
<thead>
<tr>
<th>LIBO Main Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency (MHz)</td>
<td>2998</td>
</tr>
<tr>
<td>Input Energy (MeV)</td>
<td>62</td>
</tr>
<tr>
<td>Output Energy (MeV)</td>
<td>200</td>
</tr>
<tr>
<td>Relativistic Beta</td>
<td>0.35-0.566</td>
</tr>
<tr>
<td>Average Current (nA)</td>
<td>10</td>
</tr>
<tr>
<td>Beam Pulse Duration (us)</td>
<td>5</td>
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<tr>
<td>Repetition Rate (Hz)</td>
<td>400</td>
</tr>
<tr>
<td>Beam Duty Cycle</td>
<td>0,002</td>
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<tr>
<td>Accelerating Gradient (MV/m)</td>
<td>15,3</td>
</tr>
<tr>
<td>Aperture Radius (mm)</td>
<td>4</td>
</tr>
<tr>
<td>Transverse Acceptance (mm mrad)</td>
<td>12 pi</td>
</tr>
<tr>
<td>Trapped Cyclotron Beam (%)</td>
<td>9,6</td>
</tr>
<tr>
<td>Synchronous Phase Angle (degree)</td>
<td>-19</td>
</tr>
<tr>
<td>Structure Length (m)</td>
<td>13,32</td>
</tr>
<tr>
<td>Number of cells/tank</td>
<td>13</td>
</tr>
<tr>
<td>Number of Tanks/module</td>
<td>4</td>
</tr>
<tr>
<td>Number of Modules</td>
<td>9</td>
</tr>
<tr>
<td>Number of PMQ/Tank</td>
<td>4</td>
</tr>
<tr>
<td>Quad gradient (T/m)</td>
<td>160</td>
</tr>
<tr>
<td>RF Peak Power/Module (MW)</td>
<td>≈4</td>
</tr>
<tr>
<td>RF Duty Cycle (%)</td>
<td>0,2</td>
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<tr>
<td>Number of Klystron</td>
<td>9</td>
</tr>
<tr>
<td>Vacuum (mbar)</td>
<td>10-6</td>
</tr>
</tbody>
</table>
3. LIBO-62 prototype module
LIBO-62 prototype module
3.1 Design
The final mechanical design of LIBO-62 prototype
Constraints for the design of LIBO-62 prototype

• Final goal of RF structure: constant mean accelerating electric field and simple design

• Final goal of Vacuum: $10^{-6}$ mbar

• Final goal for PMQs alignment dictated by beam dynamics: $\pm 0.1$ mm on 1.3 m module length

• Fabrication of LIBO sub-components by using standard industrial processes (machining and brazing)

• Material must be compatible with electrical and thermal conductivity, brazing processes, high vacuum, high RF fields (small size) $\rightarrow$ (low impurities)
• The coupling cells must be identical in all tanks of the module

• The accelerating cells are identical in each tank and are longer from one tank to the other ($\propto \beta$)

• The coupling slot length is the same in all the tanks of the module

• Final overall frequency: $\pm 100$ kHz ($\pm 2^\circ$C)

• Accelerating field error < 5%

• Accelerating gradient: 15.3 MV/m
Half-cell plates
Material analysis and crystallographic tests

Analysis of special copper alloys

High pure OFHC (Oxygen free) copper is used for LIBO cavity
• Low impurities
• Grain size function of temperature

Brazing tests in air and under vacuum (CERN)
Thermal stabilisation for frequency control

- The thermal cavity behaviour in steady condition is described by an isothermal cavity model.
- The power dissipation has good safety margin.
- Temperature distribution, thermal stresses and mechanical deformations of the cells will not affect irreversibly the material during the operation at full power (no permanent plastic deformations).
- The expected cavity thermal detuning under full power is between -50 and -60 kHz/°C.
- The thermal detuning can be corrected via temperature control.

The cooling system is designed accordingly.
Thermal stabilisation for frequency control

Design of cooling system

Thermal stability can be achieved with the cooling system
Bridge Coupler
End half-cell
The accelerating tank
Permanent Magnet Quadrupole (PMQs) for beam focusing

- Gradient: 160 T/m
- Length: 36 mm (good for compact accelerators), Beam hole: 5 mm
- 5 PMQs into the module (FODO structure)
- 8 blocks of Samarium-Cobalt 2-17
- Max temp. allowed: 250 °C → insertion after brazing
3.2 Construction of the copper structure at CERN
Construction sequences of LIBO prototype

Machining of 6 test half cells

TUNING & BRAZING TESTS

$\Delta f$, $\sigma$ [brazing]
$\Delta f$ [tuning range definition]

SLOT & STACK TEST

$\Delta f$ [slot]
k, ka, ke [couplings]
$\Delta f$ [end cell]
RF measurements accuracy

FINAL ENGINEERING DESIGN & DRAWINGS

Machining of cells of Tank 1

RF Measurements Tank 1 (before brazing)

Tuning cells by machining ring

Brazing of Tank 1

Check Frequency

Final tuning of Tank 1 with tuning rods insertion

Bridge Coupler Tests and machining

Assembly of the complete module, RF measurements

Brazing of the complete module and RF tests

Support and cooling design and construction

Installation of the module

Tank 1 construction

Module construction

Tank 2, 3, 4 construction
R&D on six test half-cell plates before full production at CERN

• Definition of the LIBO cells (geometrical cavity shape, coupling slot, etc.)
• Definition of machining sequences
• Definition of tuning procedures
• Definition of brazing sequences
Production of the prototype at CERN (1999-2000)

Machining on numerically controlled lathe and milling machines at

CERN Central Workshop

Typical tolerances:

± 0.02 mm
Mechanical tuning of LIBO RF cavities

- Mechanical tuning of RF cells by ring machining (compensation of cell frequency spreads)
- Lateral tuning rods insertion (→ electric field flatness)

[R. Zennaro]
Brazing of LIBO components at CERN

Brazing thermal cycle

- Brazing under vacuum (S. Mathot, CERN)
- Filler metal: silver based alloys
- Four brazing temperatures ranging between 850 and 750 °C
- By capillarity with wires and foils techniques
- Deep cleaning before brazing

The brazing technique is fundamental for a good joint and it is connected to:
RF contact, vacuum tightness, thermal conductivity
Brazing of the tank
Brazing of the prototype

Ultra-sound tests for filler metal distribution after brazing
Results of electric field distribution after final brazing and RF tuning

The accelerating field distribution in the four tanks of LIBO shows an uniformity around 3% [M. Weiss, R. Zennaro]
3.3 Tests
- Metrology
- Vacuum
- Power tests
- Acceleration tests
Metrology at CERN Central Workshop

→ Alignment of the PMQs inside LIBO

Constraints from beam dynamics:

max transverse PMQs misalignment

±0.1 mm

(module length 1.3 m)
Vacuum tests at CERN

Main vacuum constraints:
- $10^{-6}$ mbar with very low impurities (clean condition)
- He-leak detection
RF power tests at LIL tunnel (CERN, 2000)
The installation engineering design
Prototype installation at CERN

RF power source:
the 3 GHz klystron at LIL tunnel (CERN)

Cooling system for thermal stabilisation
Control room for RF power tests at CERN

DAQ for RF power tests at CERN
Power tests:

RF conditioning story (CERN 2000)
RF power tests at CERN: multipacting effect into LIBO when the RF power is injected

$P_{RF} = 4\ \text{MW} \rightarrow 7\ \text{MW}$
(Repetition Rate: 100 Hz, pulse length: 2 $\mu$sec)
RF power tests (CERN):
stable condition after RF conditioning
Acceleration tests at LNS-INFN, Catania (2001-2002)
- 62 MeV proton Superconducting Cyclotron (Catania)

- 3 GHz klystron from IBA/Scanditronix

- Test conditions:
  - pulse length 5 μsec
  - repetition rate 10 Hz
  - input current: 1 nA

Energy spectrum for an accelerated proton beam of 73 MeV, with 3.4 MW of RF power injected into LIBO [Prof. De Martinis, Milan]
3.3 Conclusions
The electric field distribution and the acceleration rate and particles motion, can be controlled inside of the design specifications.

The accelerating structure, after a short conditioning, is free from electrical breakdown and the final vacuum levels are better of the design specifications.
An accelerating gradient of 29 MV/m has been reached, better than the design value (15.3 MV/m).

- Construction procedures and mechanical tolerances of the accelerating structure allow covering the required physical performances.
The prototype construction and tests of the LIBO collaboration prove that *LIBO works in agreement with the design and standard industrial technology at “low costs” can be adopted for fabrication*, even for this unusual high frequency 3 GHz proton accelerating structure.