Université Claude Bernard Lyon I

THESE

pour l’obtention

du DIPLOME DE DOCTORAT

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

Paolo Berra

14/10/2005

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1. Introduction

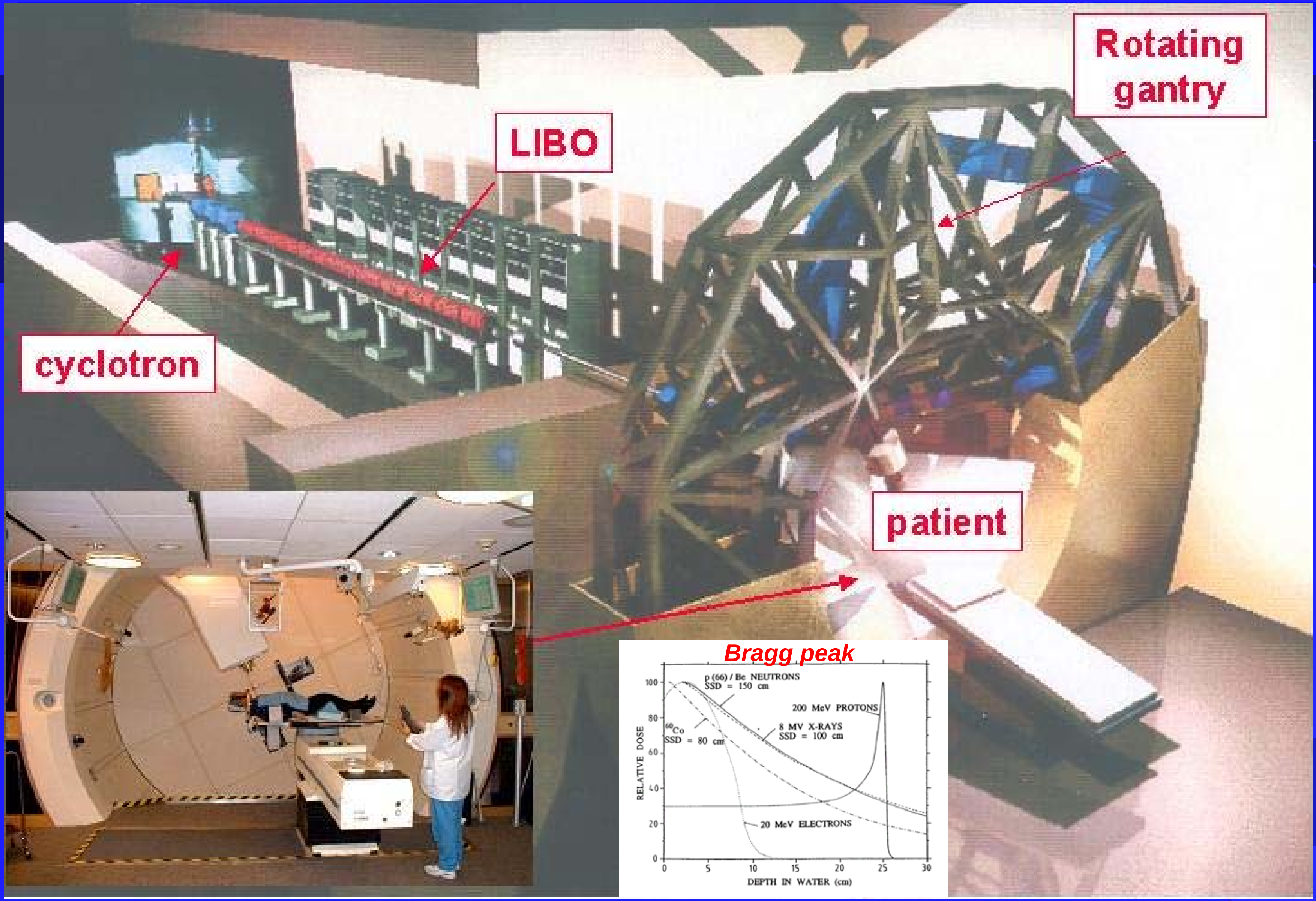
LIBO concepts

- **A new compact LInac BOoster for hadrontherapy**

[Ugo Amaldi, *Hadrontherapy in oncology*, U. Amaldi and B. Larsson eds, Elsevier, 1994 and

Mario Weiss et al, *High frequency proton linac*, in *The Green Book*, U. Amaldi, M. Grandolfo, L. Picardi eds, 1996)]

- **LIBO boosts the energy of proton beams extracted from a cyclotron up to 200 MeV for deep-seated tumours**


Rotating gantry
LIBO
cyclotron
patient
Bragg peak
p (66) / Be NEUTRONS
SSD = 150 cm
200 MeV PROTONS
^{60}Co
SSD = 80 cm
8 MV X-RAYS
SSD = 100 cm
20 MeV ELECTRONS
RELATIVE DOSE
0
20
40
60
80
100
DEPTH IN WATER (cm)
0
5
10
15
20
25
30

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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D. Davino(5), C. De Martinis(4), D. Giove(4),
M.R. Masullo(5), E. Rosso(2), B. Szeless(2), D. Toet(1),
V. Vaccaro(5), M. Vretenar(2), M. Weiss(1), R. Zennaro(1).

(1) TERA Foundation
(2) CERN
(3) Milan-Bicocca University
(4) INFN and Milan University
(5) INFN and Naples University

Main Milestones for the LIBO prototype:

- **Design**

- **Construction at CERN in the frame of the Technology Transfer Division (<u>Dr H. F. Hoffmann</u>)**

- **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?

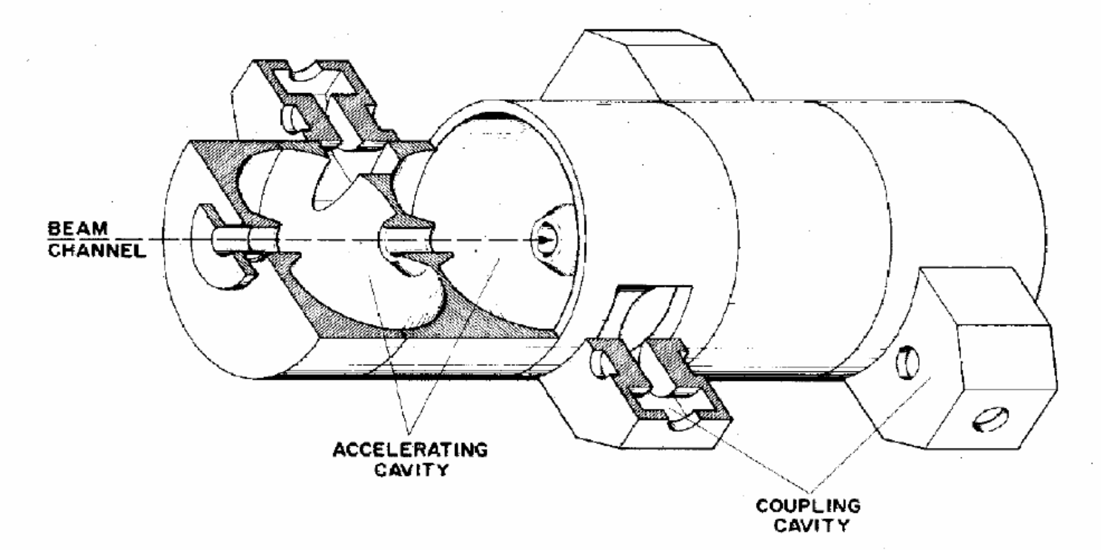
U. Amaldi → Hadrontherapy program

→ PACO project (COmpact Accelerators Project for protontherapy), 1993.

- Acceleration of 2 x 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 $\beta > 0.4$.



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/cm^2 - 20 g/cm^2
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 cm^2)

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

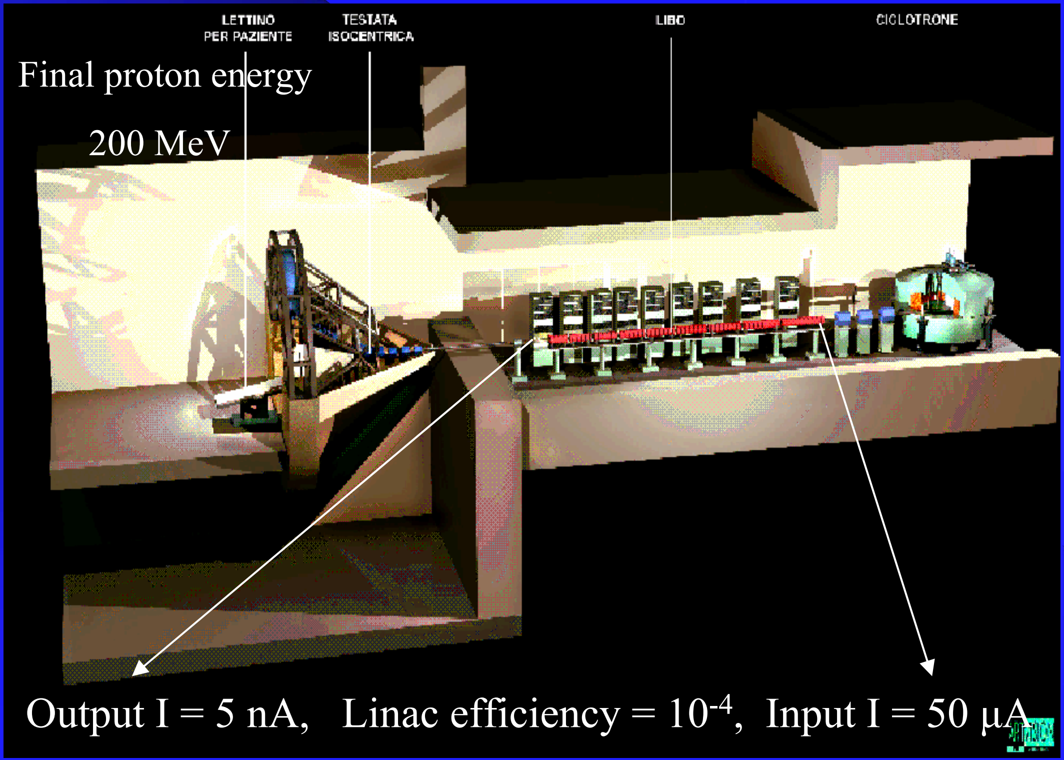
⇩

It fits the active scanning application

How LIBO works

- Total efficiency cyclotron-linac: order of 10^{-4} (trapped beam ~10%, duty factor 0.2%)
- Input current from the cyclotron: 50 µA

→ Output current from LIBO: 5 nA → enough for cancer therapy



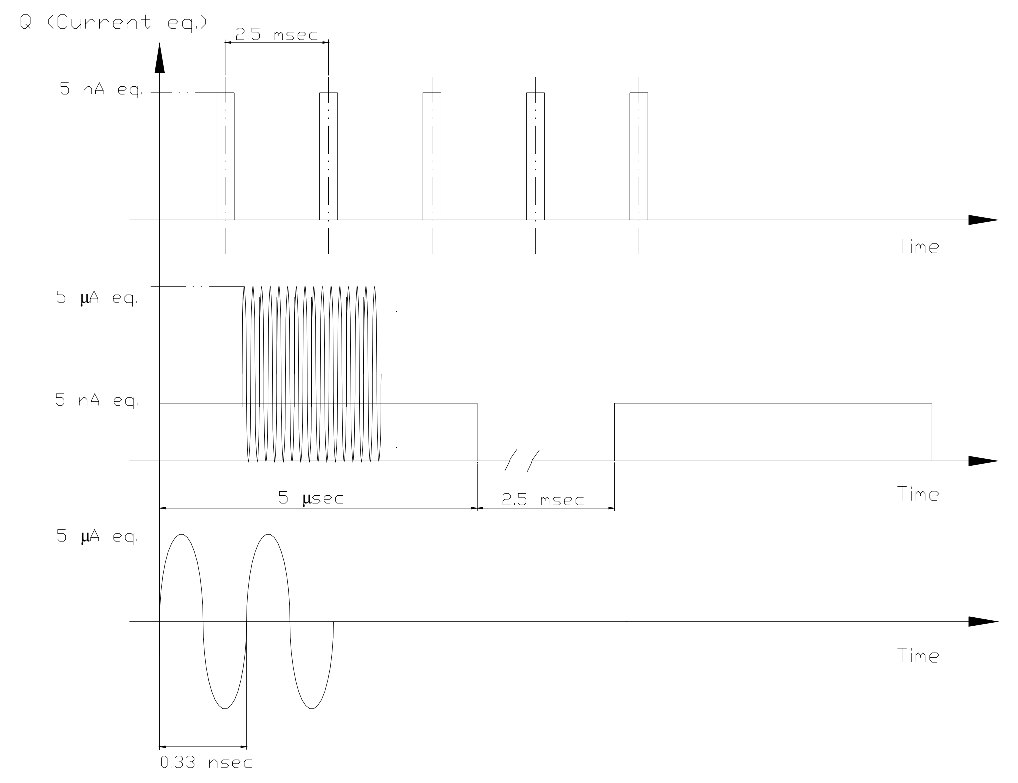
Final proton energy

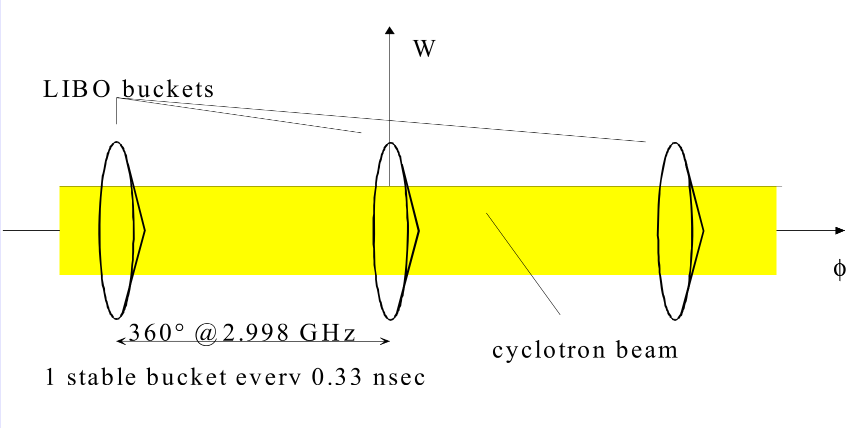
200 MeV

Output I = 5 nA, Linac efficiency = 10^{-4}, Input I = 50 µA

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

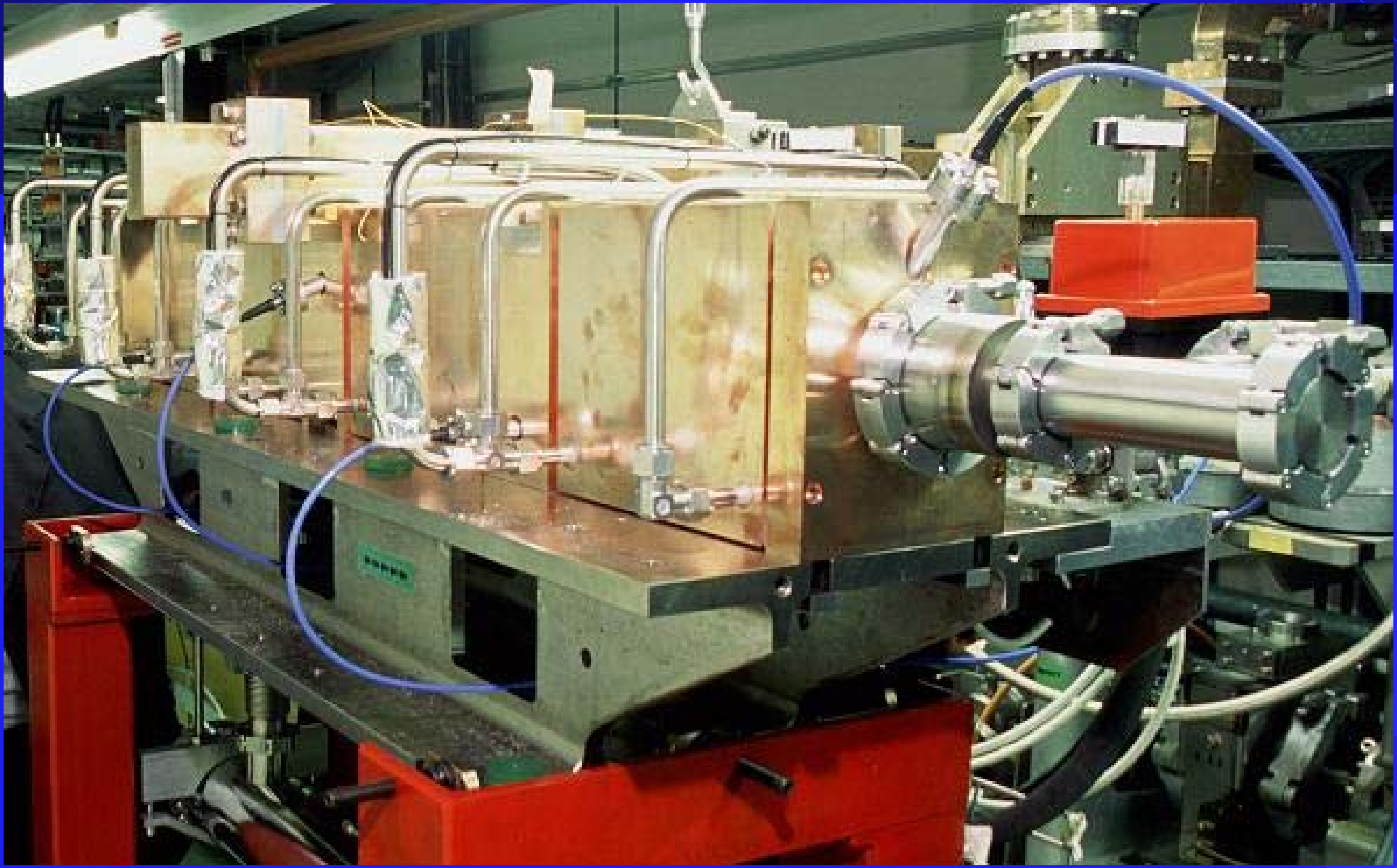
LIBO-62: basic description

- 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

LIBO Main Parameters	Value
Operating Frequency (MHz)	2998
Input Energy (MeV)	62
Output Energy (MeV)	200
Relativistic Beta	0.35-0.566
Average Current (nA)	10
Beam Pulse Duration (us)	5
Repetition Rate (Hz)	400
Beam Duty Cycle	0,002
Accelerating Gradient (MV/m)	15,3
Aperture Radius (mm)	4
Transverse Acceptance (mm mrad)	12 pi
Trapped Cyclotron Beam (%)	9,6
Synchronous Phase Angle (degree)	-19
Structure Length (m)	13,32
Number of cells/tank	13
Number of Tanks/module	4
Number of Modules	9
Number of PMQ/Tank	4
Quad gradient (T/m)	160
RF Peak Power/Module (MW)	≈4
RF Duty Cycle (%)	0,2
Number of Klystron	9
Vacuum (mbar)	10-6

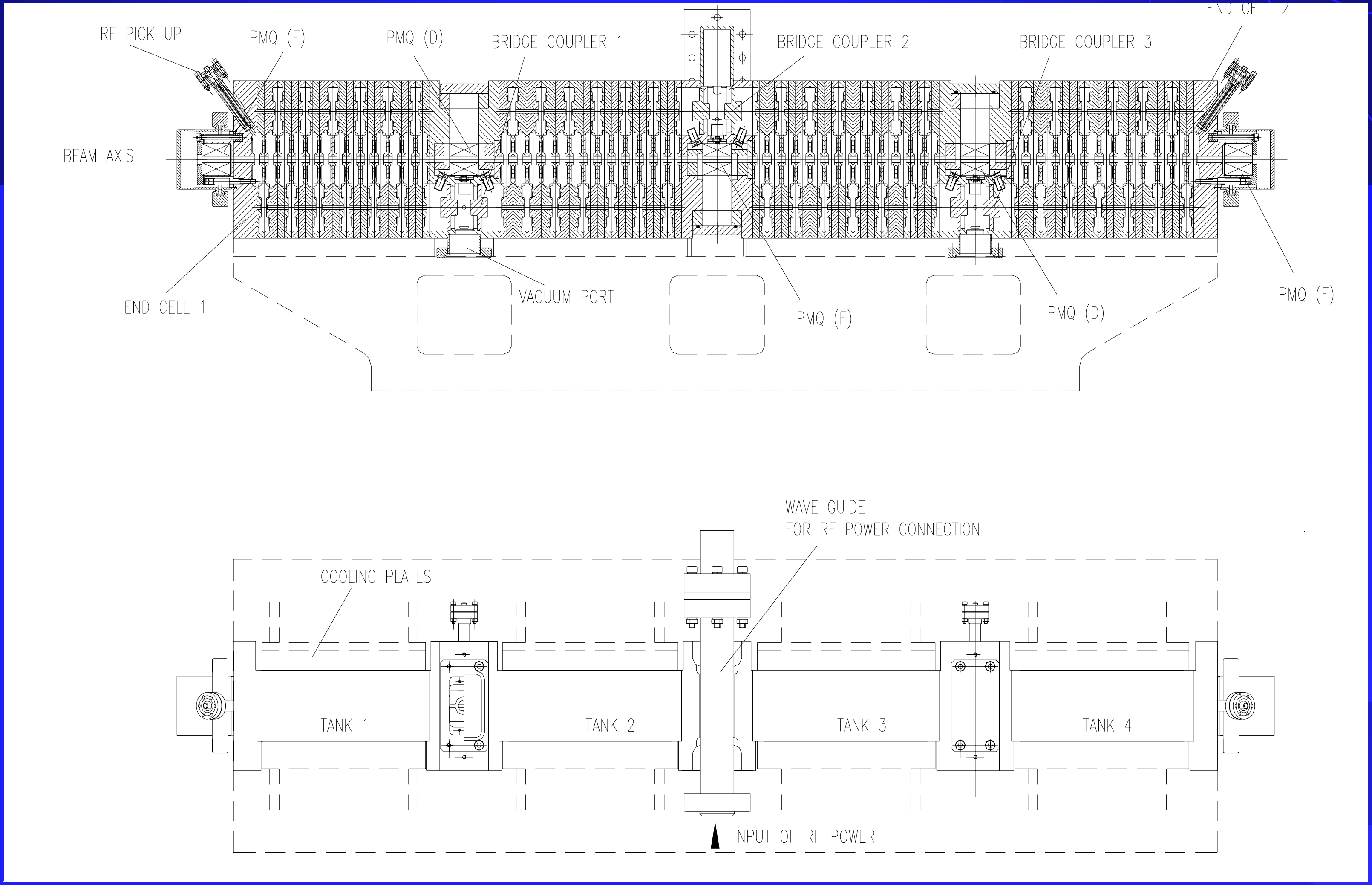
3. LIBO-62 prototype module

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: ±0.1 mm on 1.3 m module length*

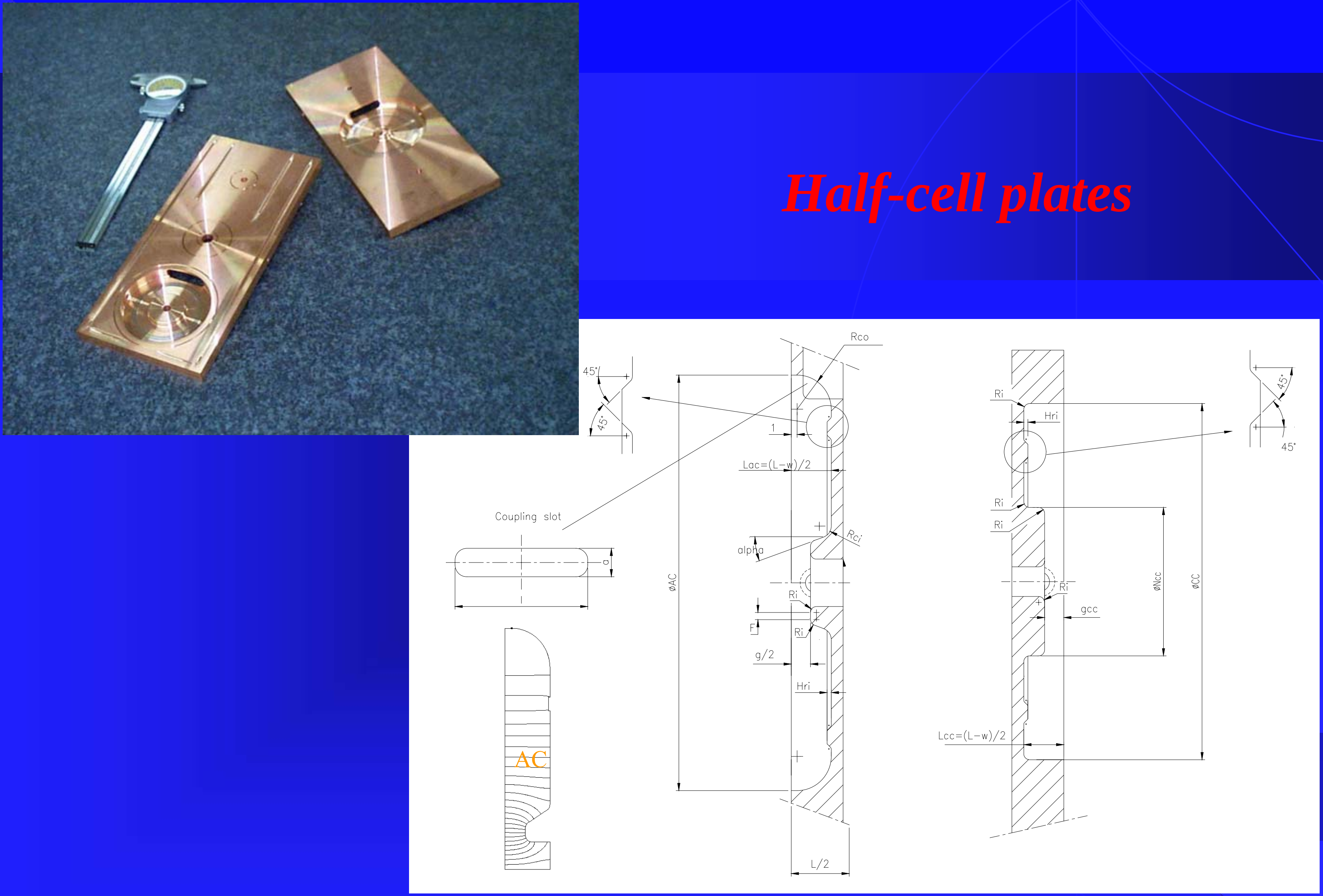
- *Fabrication of LIBO sub-components by using standard industrial processes (machining and brazing)*

- *Material must be compatible with electrical and thermal conductivity, brazing processes, high vacuum, high RF fields (<u>small size</u>) → (<u>low impurities</u>)*

Basics on conceptual design of the prototype

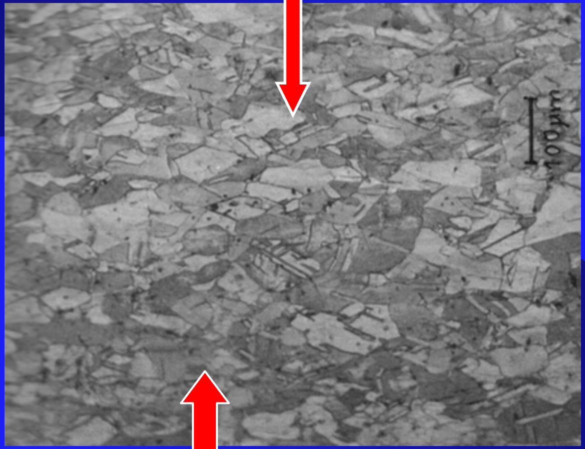
- ***The coupling cells must be identical in all tanks of the module***
- ***The accelerating cells are identical in each tank and are longer from one tank to the other*** (*$\propto \beta$* ***)***
- ***The coupling slot length is the same in all the tanks of the module***
- ***Final overall frequency: ±100 kHz (±2°C)***
- ***Accelerating field error < 5%***
- ***Accelerating gradient: 15.3 MV/m***

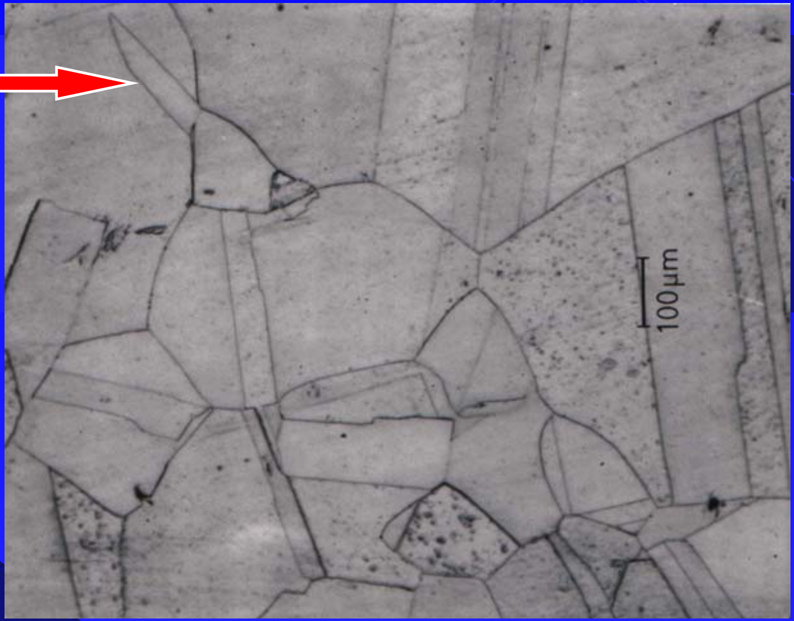
Half-cell plates



Material analysis and crystallographic tests

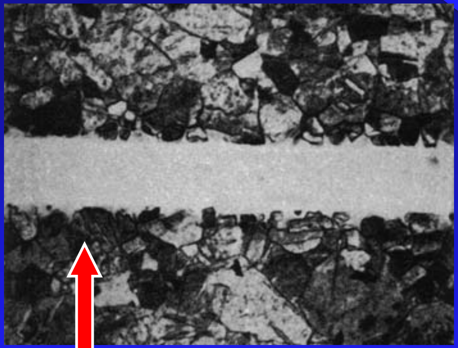
Analysis of special copper alloys

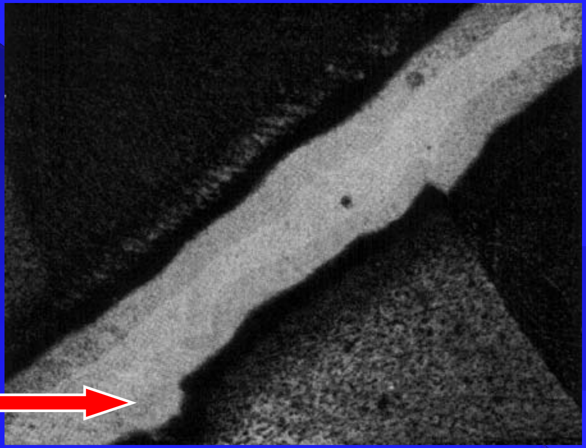




High pure OFHC (Oxygen free) copper is used for LIBO cavity

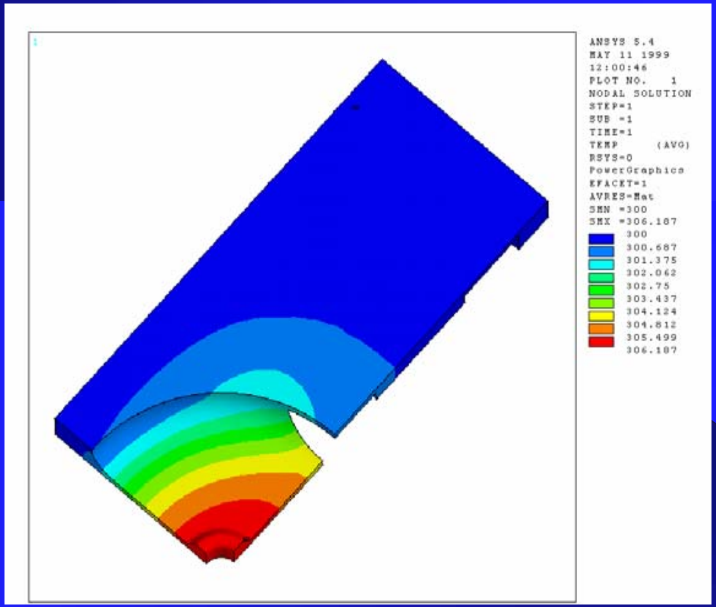
- Low impurities
- Grain size function of temperature





Brazing tests in air and under vacuum (CERN)

Thermal stabilisation for frequency control

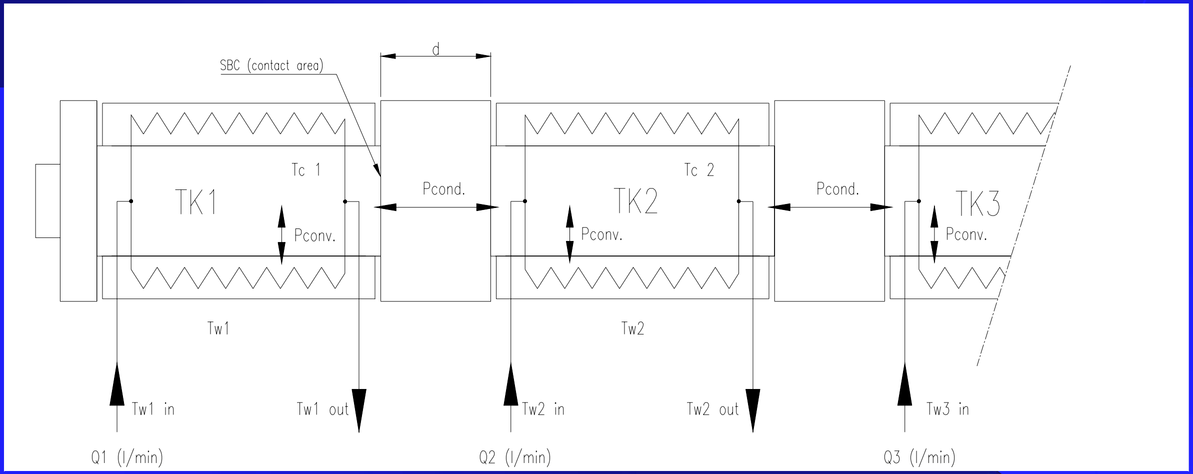


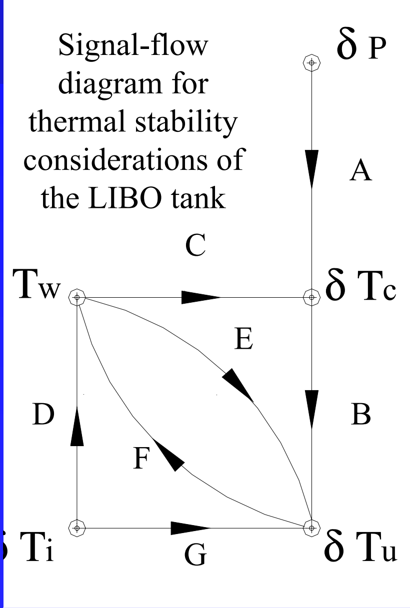
- The thermal cavity behaviour in steady condition is described by an isothermal cavity model.
- The power dissipation has good safety margin.
- Temperature distribution, thermal stresses and mechanical deformations of the cells will not affect irreversibly the material during the operation at full power (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

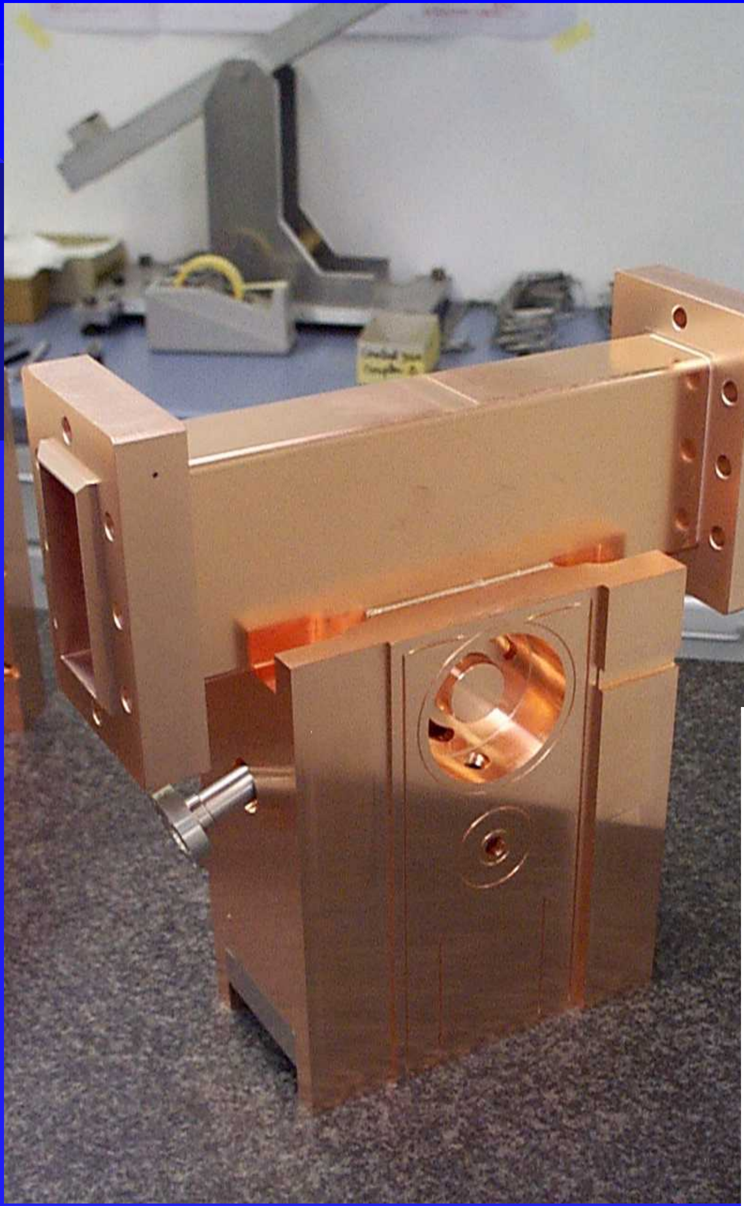


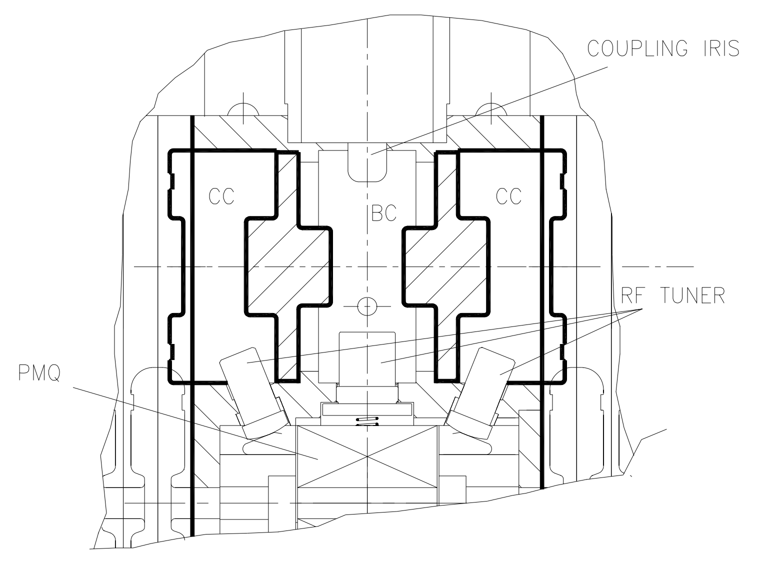

Signal-flow diagram for thermal stability considerations of the LIBO tank

$$\begin{bmatrix}\delta\ T_c(s)\\ \delta\ T_w(s)\\ \delta\ T_o(s)\end{bmatrix}=\underbrace{\frac{\begin{bmatrix}\left(s+\frac{1}{\tau_w}+\frac{2}{\tau_c}\right)\cdot\frac{1}{K^*\cdot\tau_c} & \frac{2}{\tau_0\cdot\tau_c}\\ \frac{1}{K^*\cdot\tau_c\cdot\tau_w} & \left(s+\frac{1}{\tau_c}\right)\cdot\frac{2}{\tau_0}\\ \frac{2}{K^*\cdot\tau_c\cdot\tau_w} & \left(s+\frac{1}{\tau_c}\right)\cdot\frac{4}{\tau_0}-\det(sI-A)\end{bmatrix}}{\det(sI-A)}}_{F(\mathrm{s})}\cdot\begin{bmatrix}\delta\ P(s)\\ \delta\ T_i(s)\end{bmatrix}$$

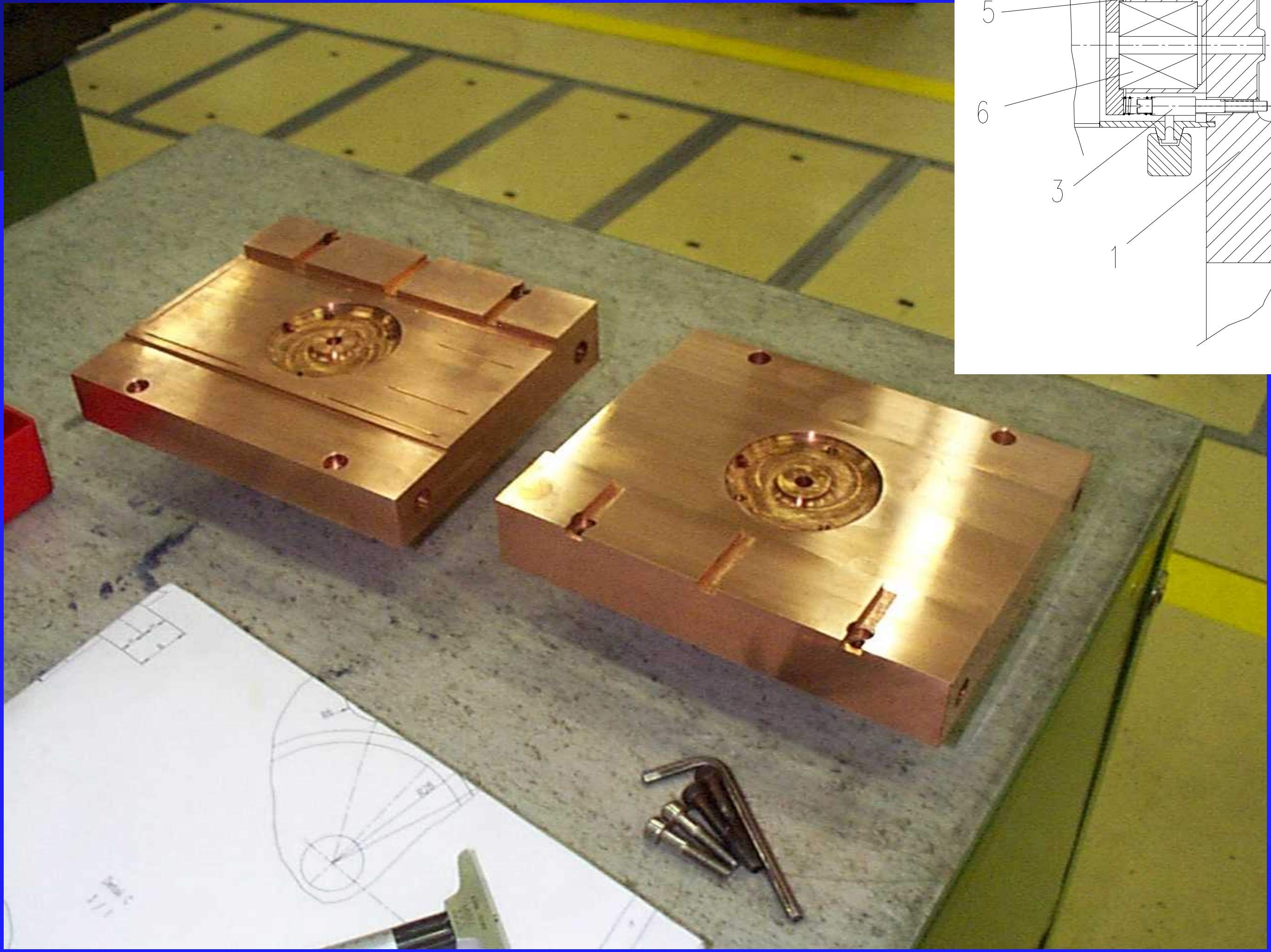
→ Thermal stability can be achieved with the cooling system

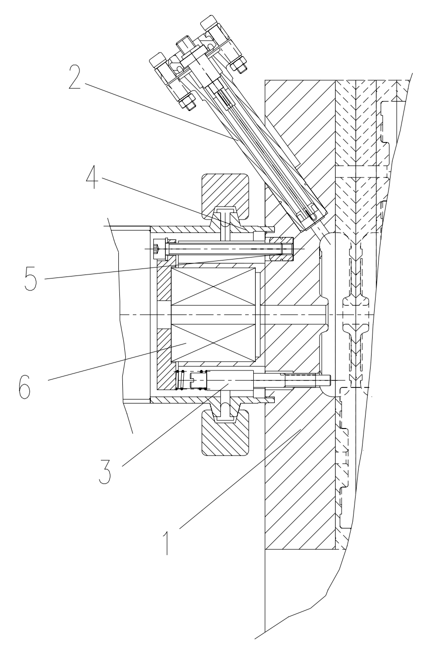
Bridge Coupler



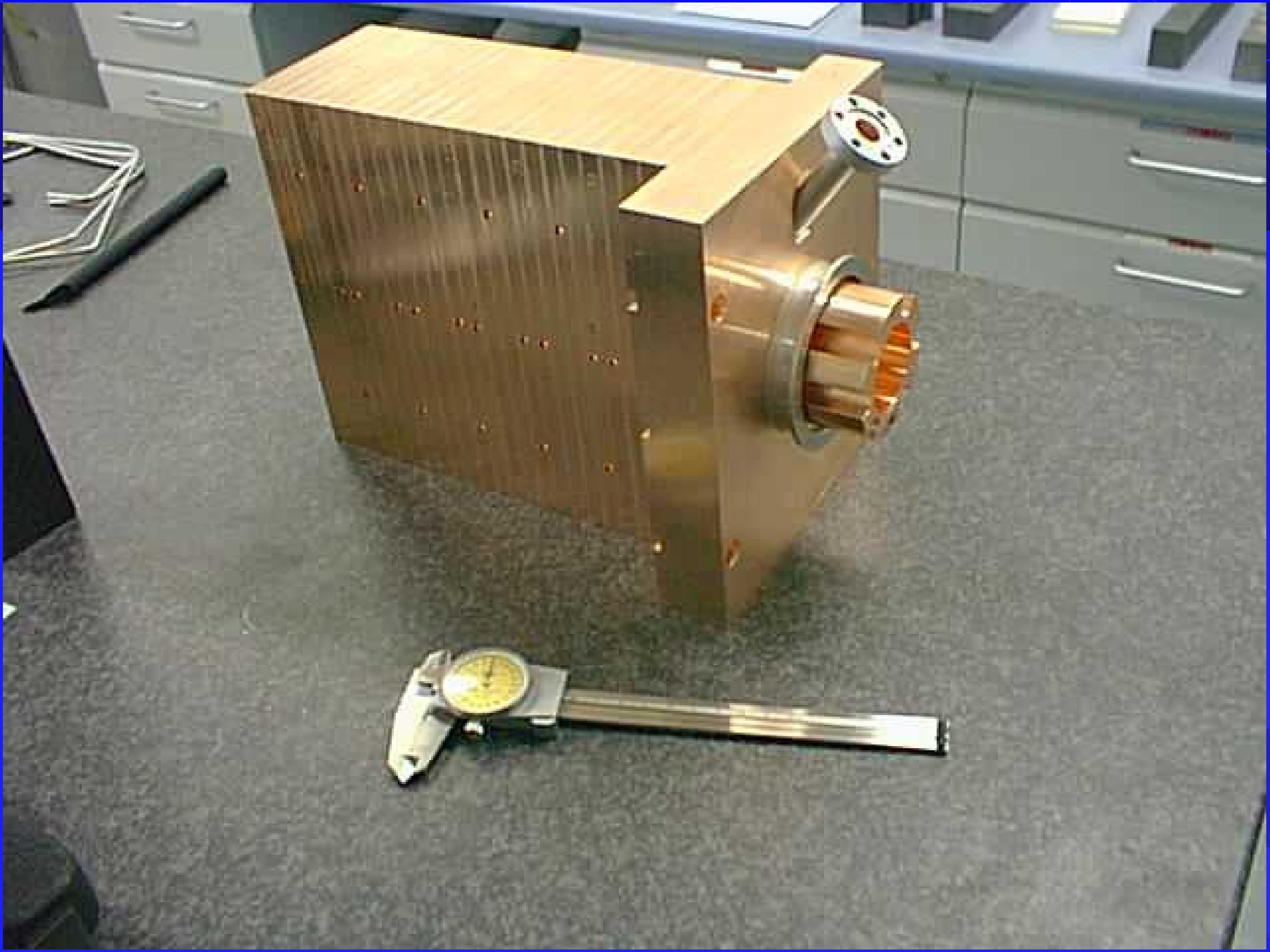


End half-cell

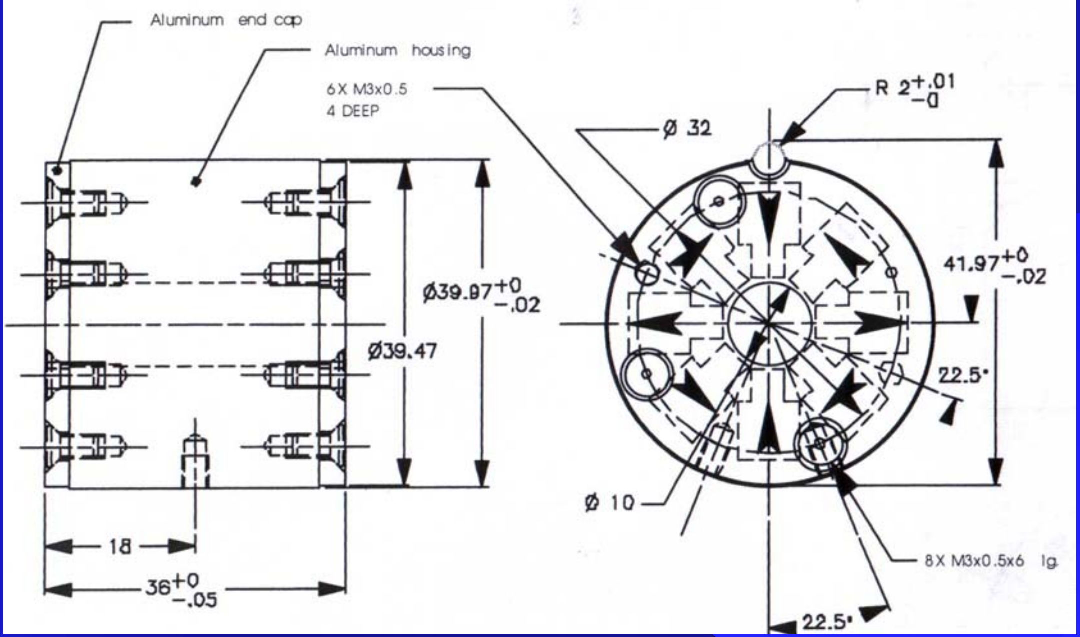




The accelerating tank



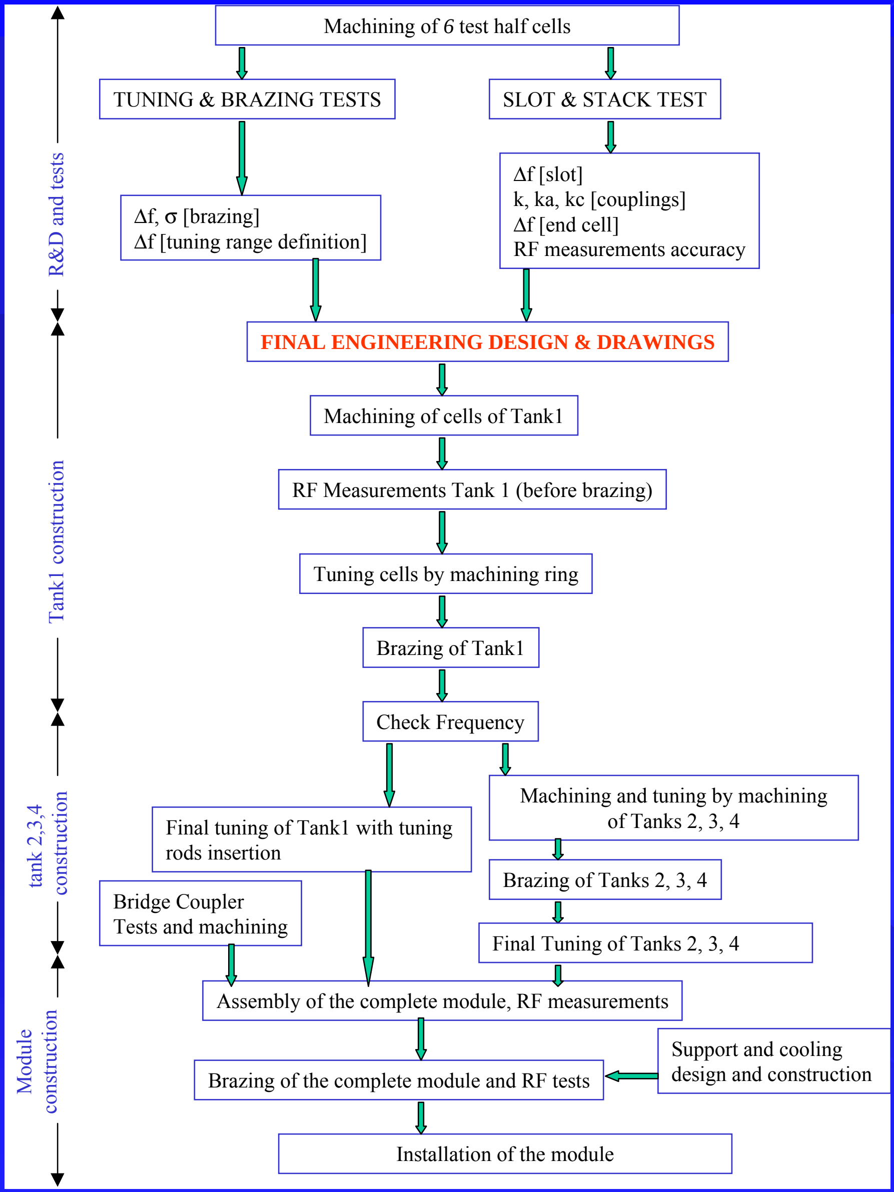
Permanent Magnet Quadrupole (PMQs) for beam focusing



- 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



R&D and tests

Machining of 6 test half cells

TUNING & BRAZING TESTS

SLOT & STACK TEST

Δf, σ [brazing]
Δf [tuning range definition]

Δf [slot]
k, ka, kc [couplings]
Δf [end cell]
RF measurements accuracy

Tank1 construction

FINAL ENGINEERING DESIGN & DRAWINGS

Machining of cells of Tank1

RF Measurements Tank 1 (before brazing)

Tuning cells by machining ring

Brazing of Tank1

Check Frequency

tank 2,3,4 construction

Final tuning of Tank1 with tuning rods insertion

Machining and tuning by machining of Tanks 2, 3, 4

Brazing of Tanks 2, 3, 4

Final Tuning of Tanks 2, 3, 4

Bridge Coupler
Tests and machining

Module construction

Assembly of the complete module, RF measurements

Support and cooling design and construction

Brazing of the complete module and RF tests

Installation of the module

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**

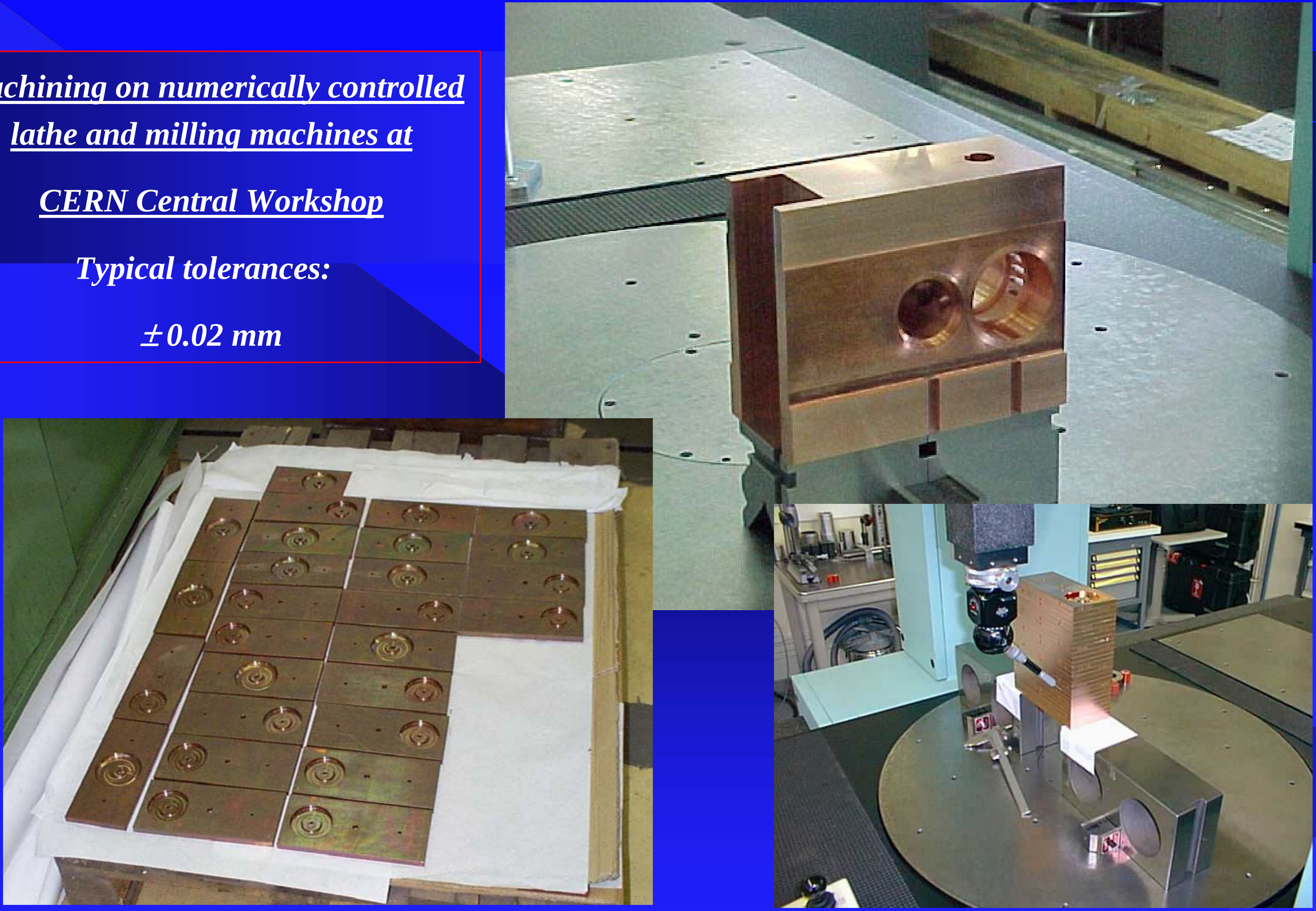
Production of the prototype at CERN (1999-2000)

Machining on numerically controlled lathe and milling machines at

CERN Central Workshop

Typical tolerances:

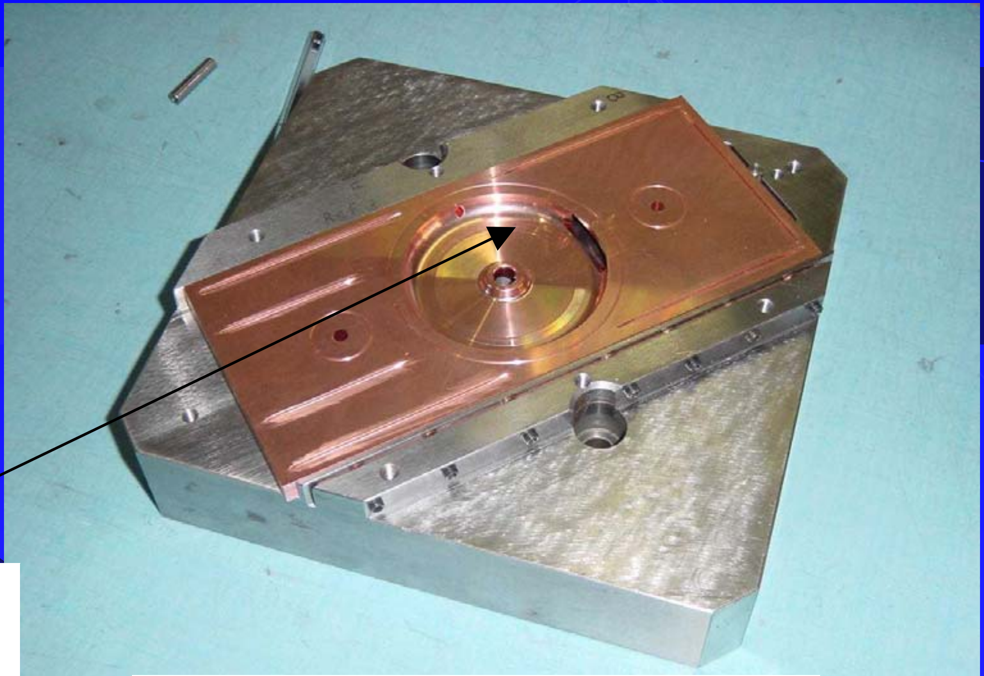
±0.02 mm

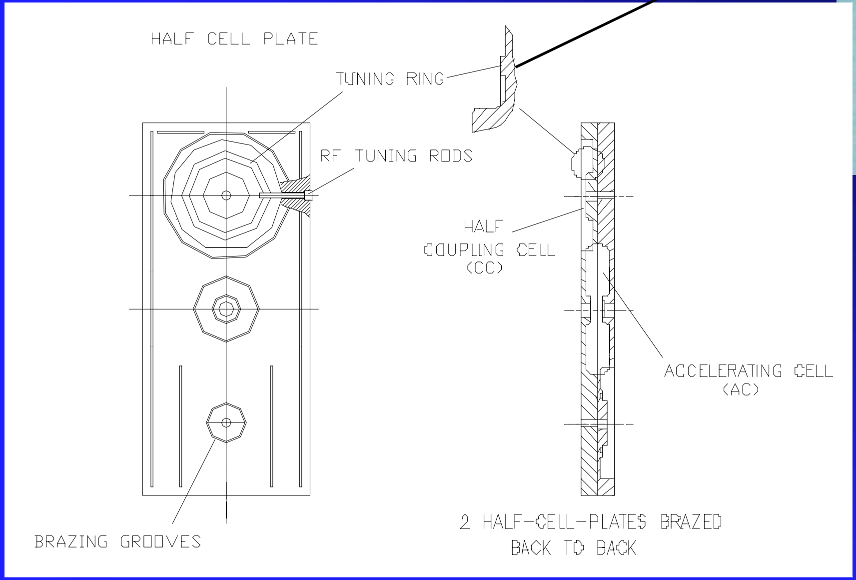


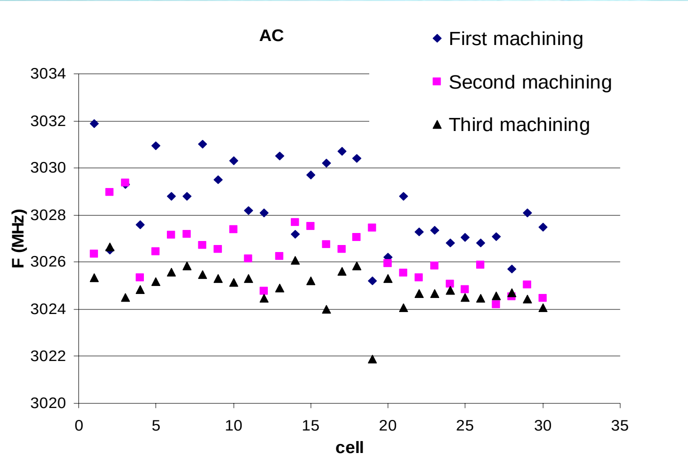
Mechanical tuning of LIBO RF cavities

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

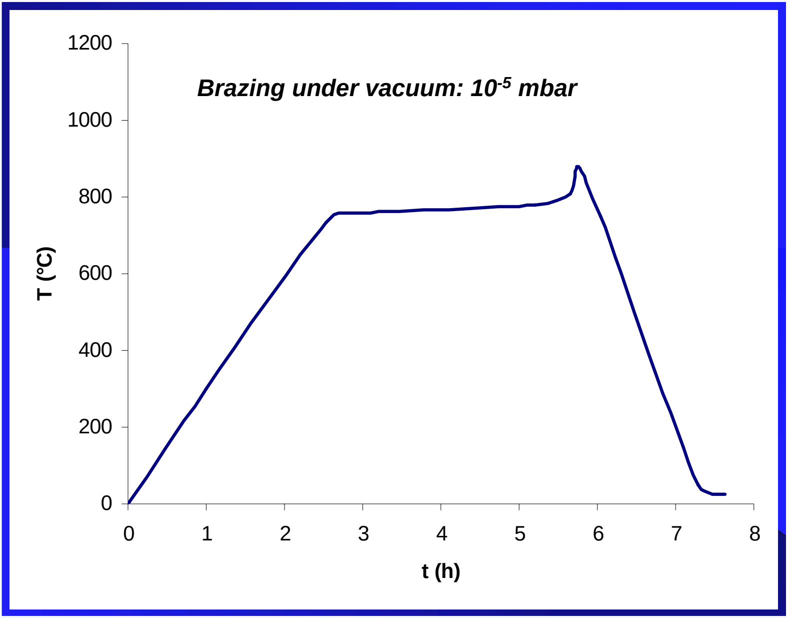
[R. Zennaro]





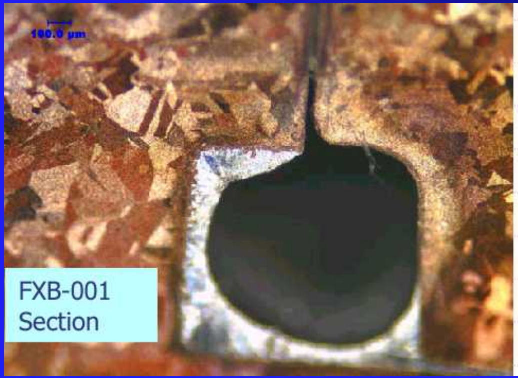


Brazing of LIBO components at CERN

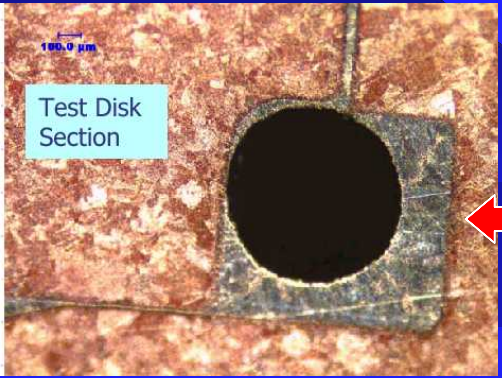


Brazing
thermal cycle

- *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*



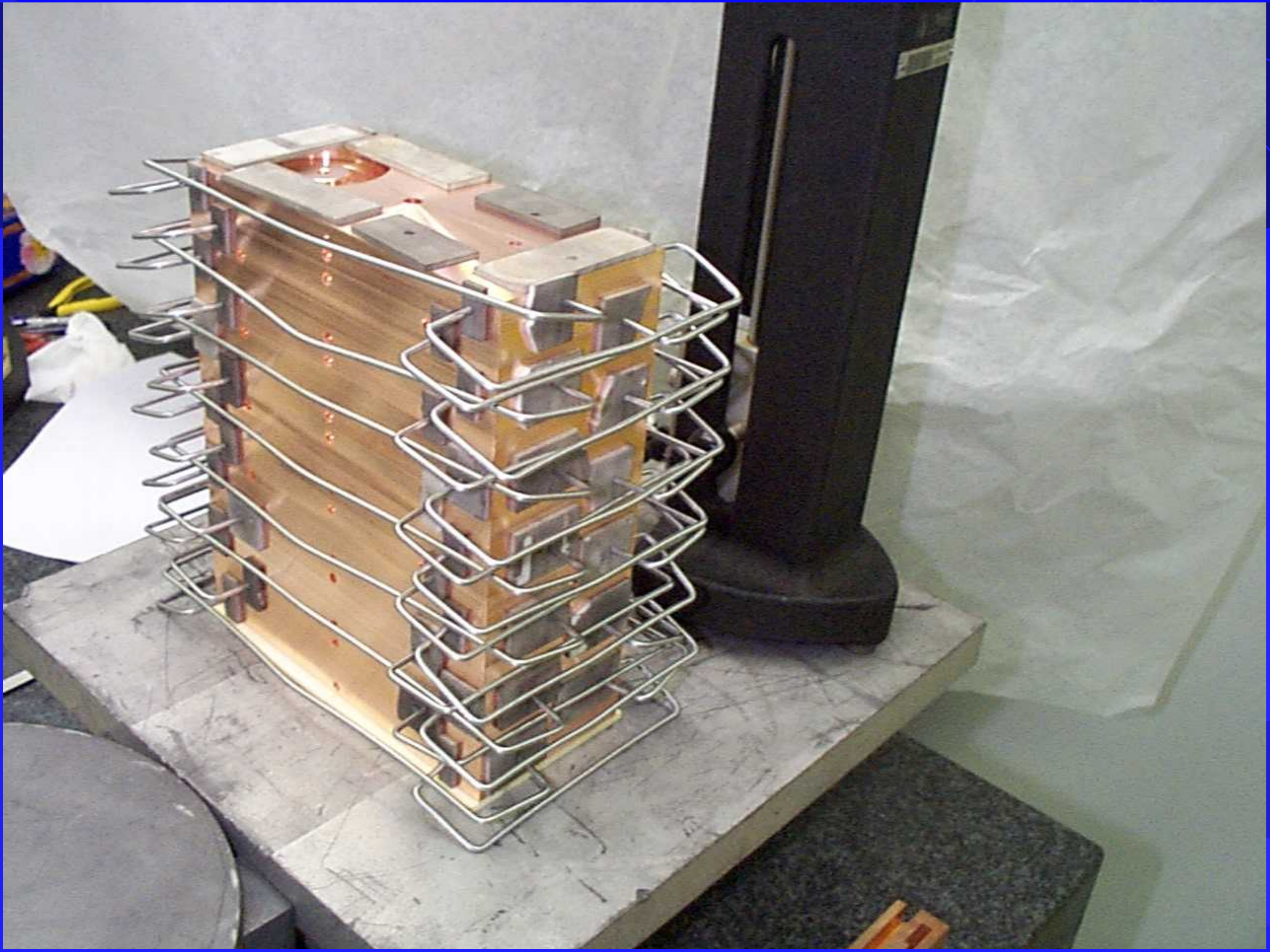
FXB-001 Section



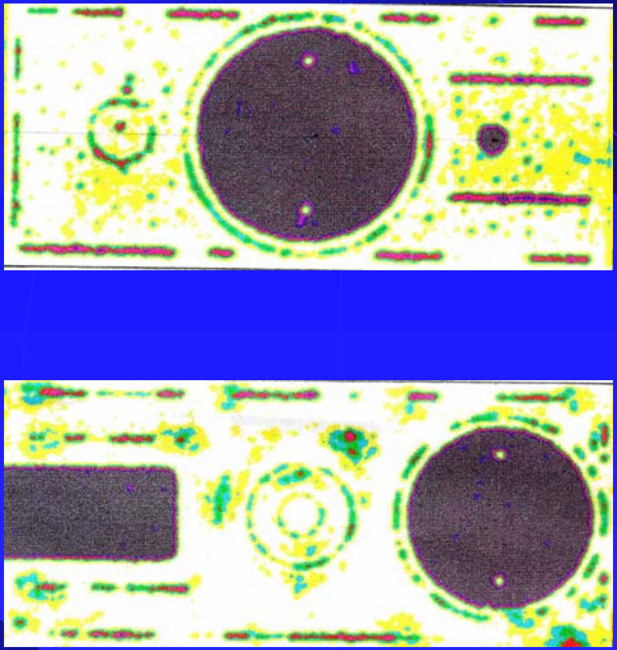
Test Disk Section

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

Brazing of the tank



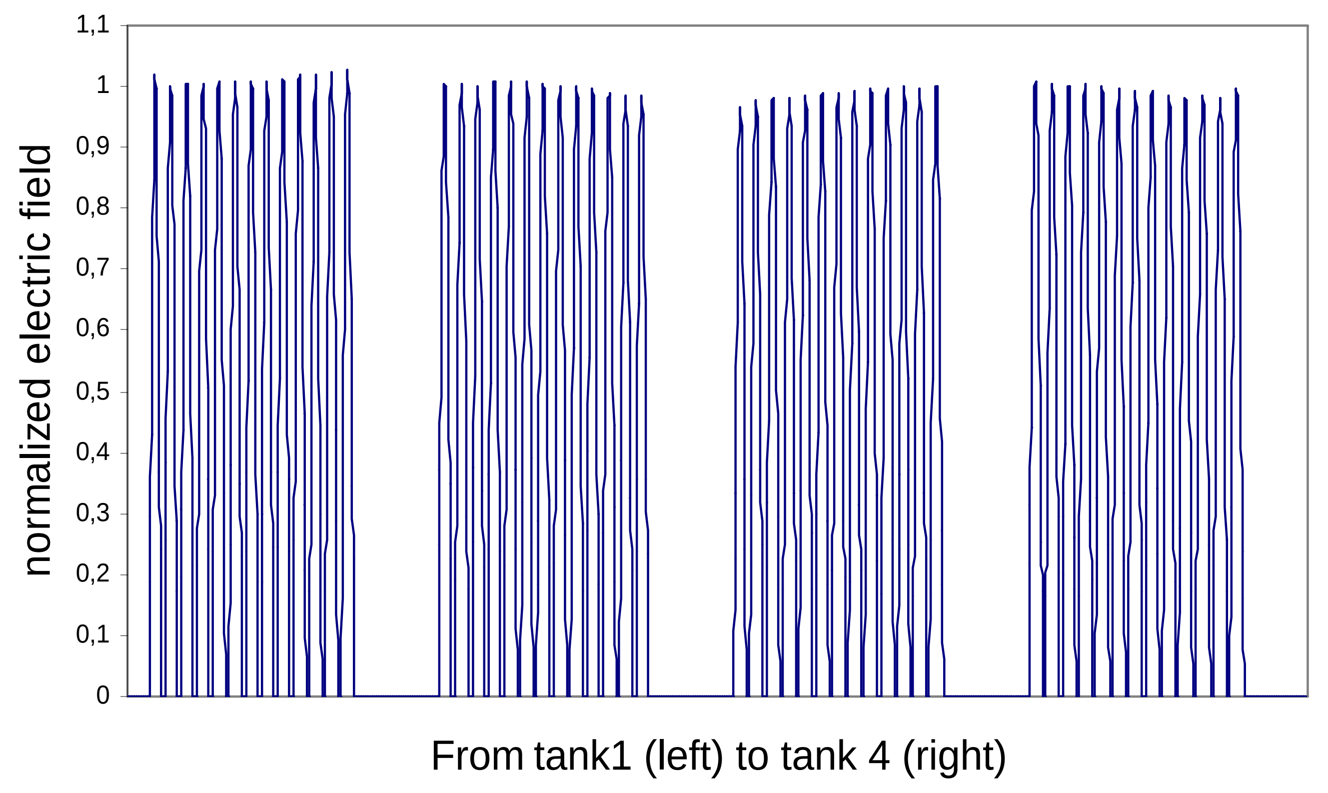
Brazing of the prototype



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]

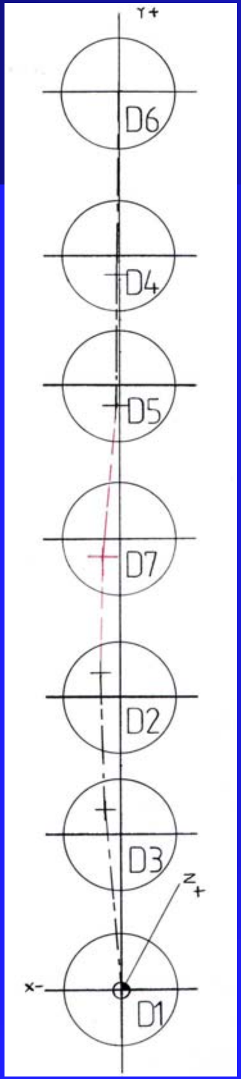


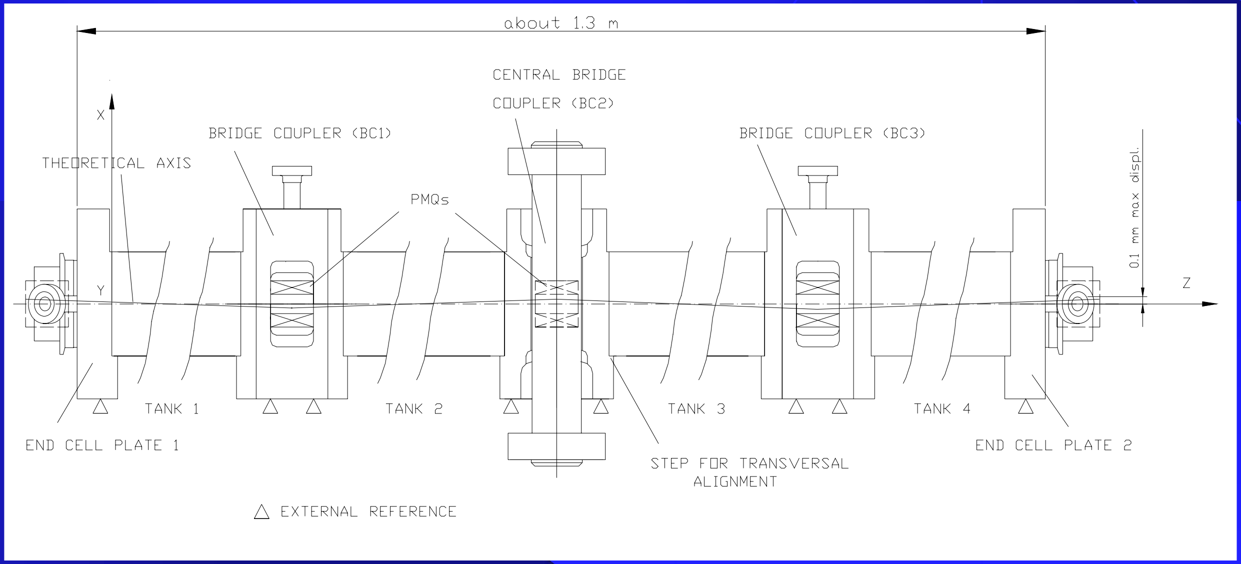
3.3 Tests

- Metrology
- Vacuum
- Power tests
- Acceleration tests

Metrology at CERN Central Workshop

→ Alignment of the PMQs inside LIBO



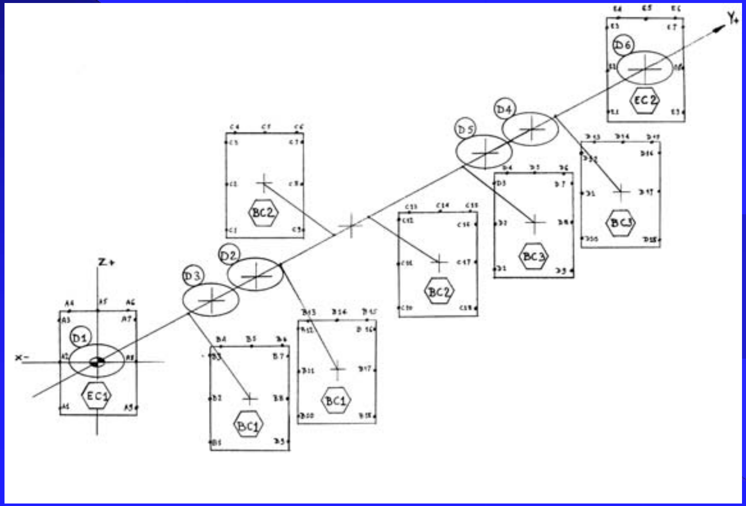


__Constraints from beam dynamics:__

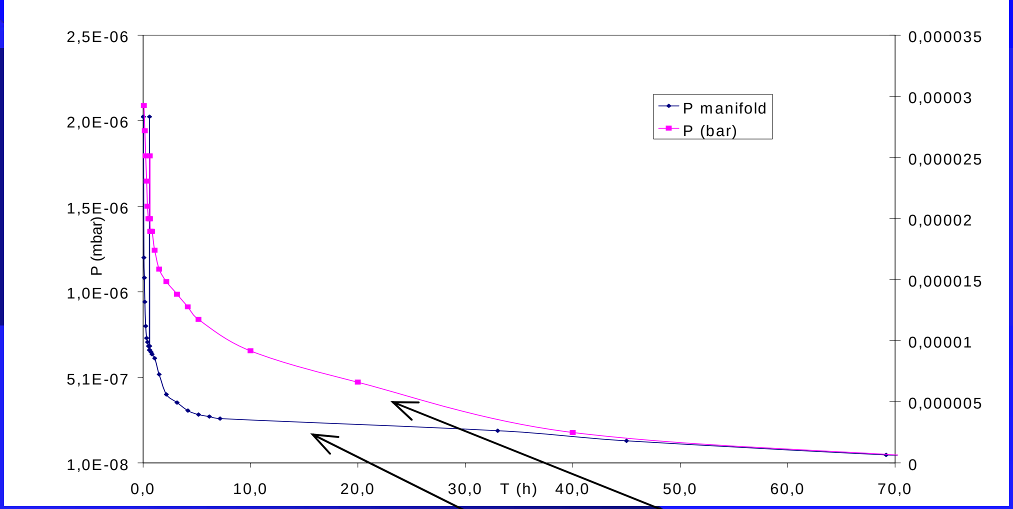
max transverse PMQs misalignment

±0.1 mm

(module length 1.3 m)

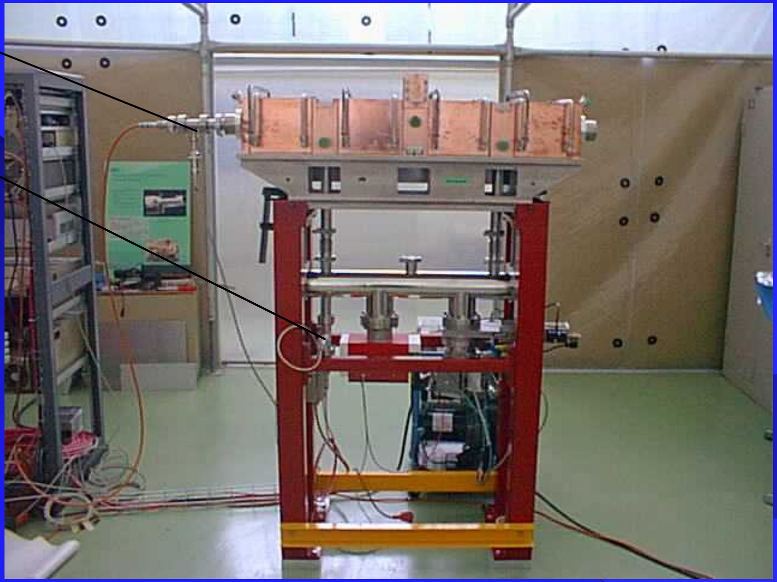


Vacuum tests at CERN

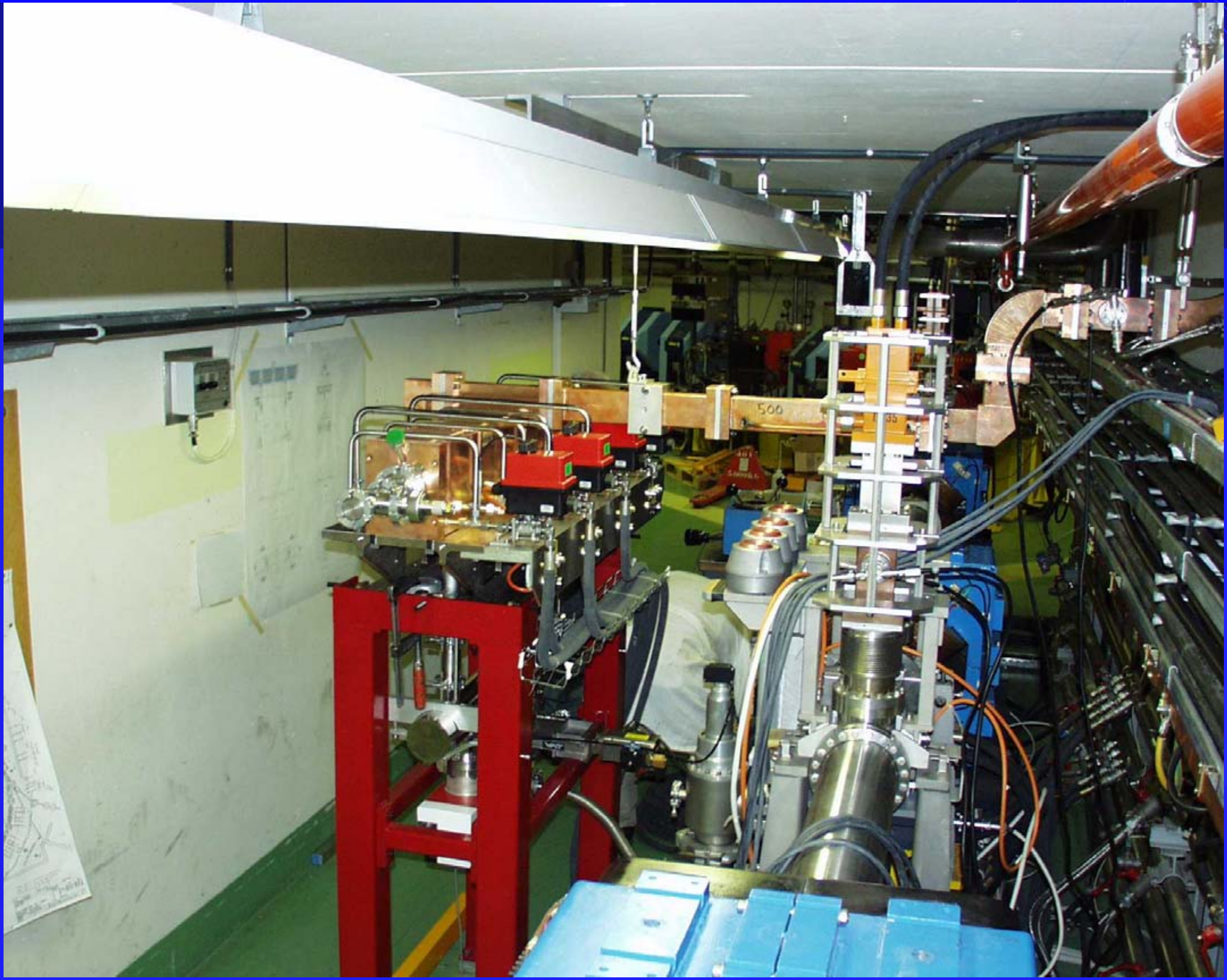


Main vacuum constraints:

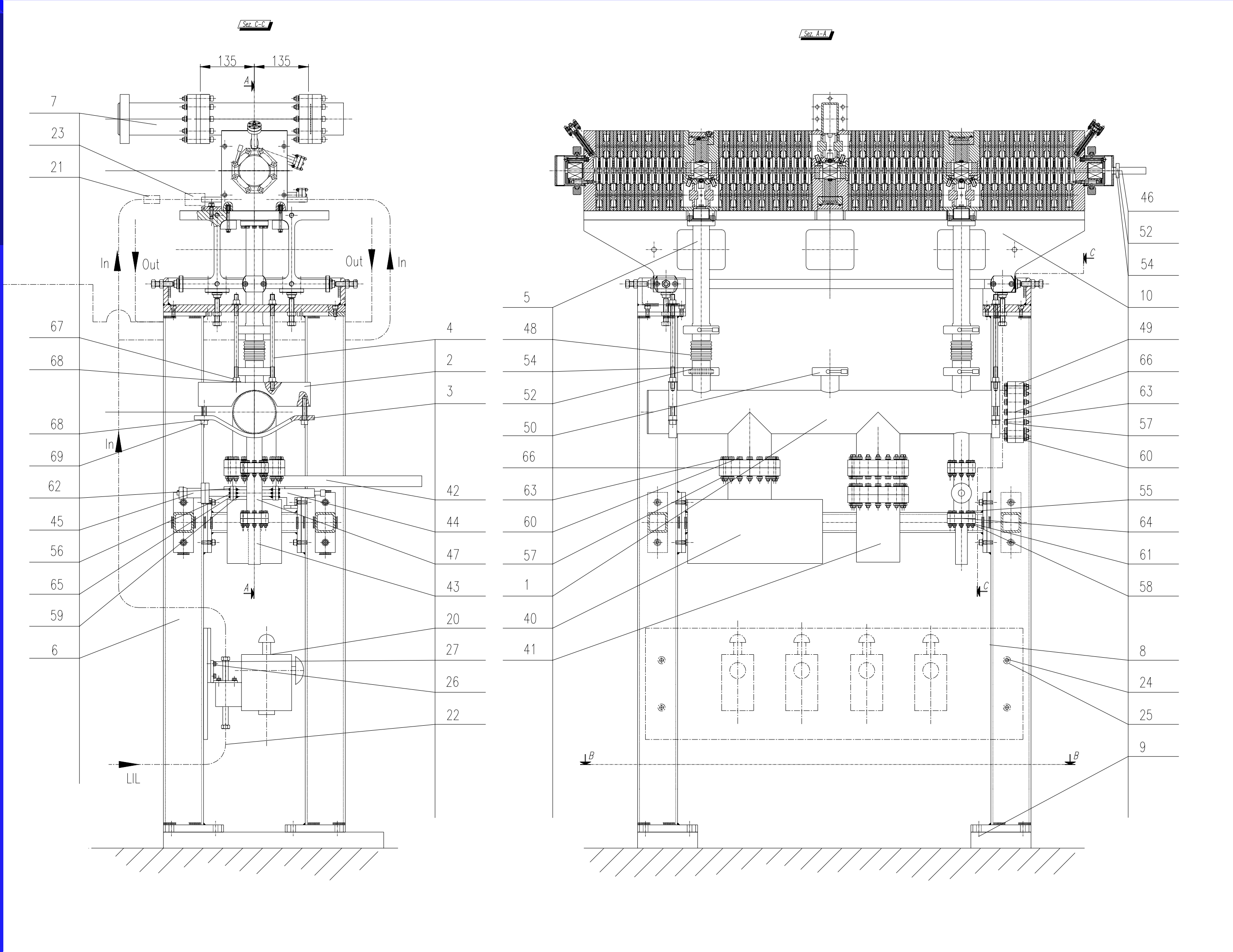
- ***10^{-6} mbar with very low impurities (<u>clean condition</u>)***
- ***He-leak detection***



RF power tests at LIL tunnel (CERN, 2000)



The installation engineering design

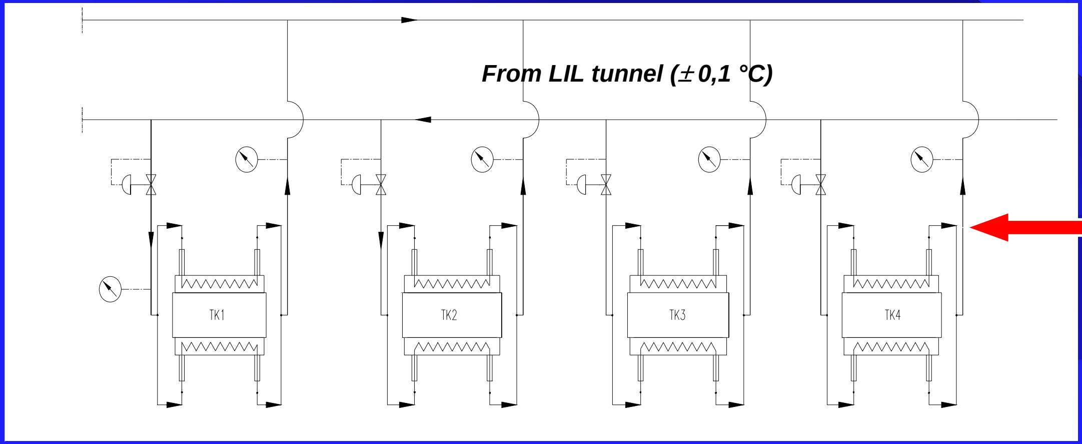


Prototype installation at CERN

RF power source:

the 3 GHz klystron at

LIL tunnel (CERN)

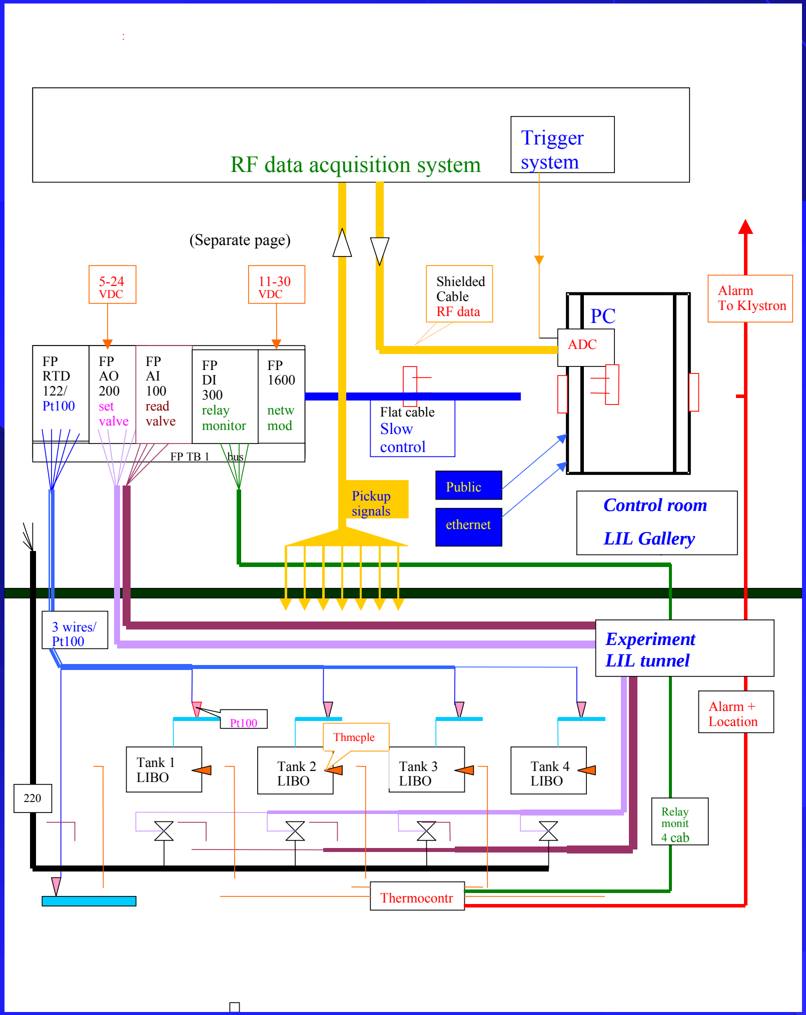


Cooling

system for thermal

stabilisation

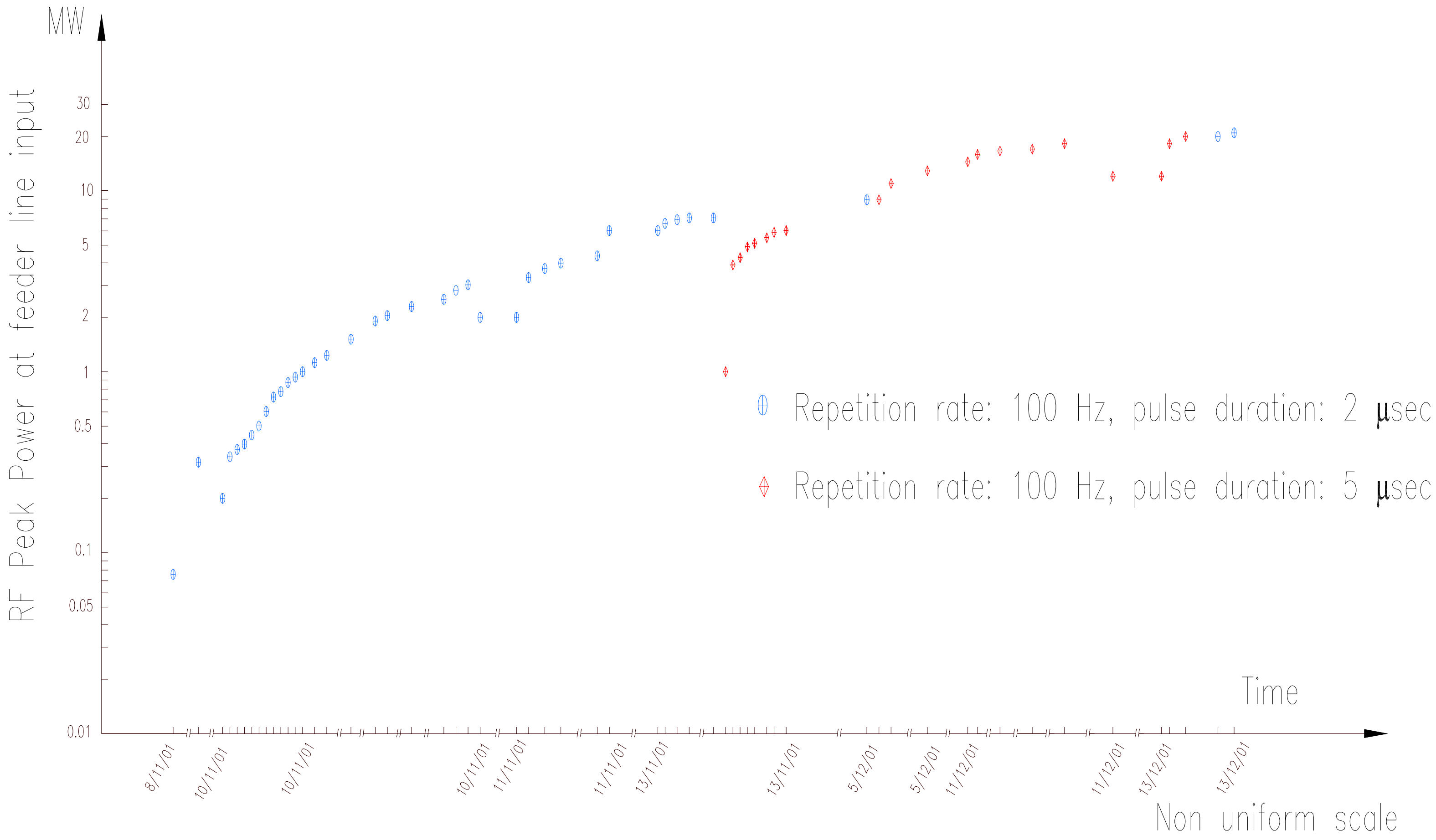
Control room for RF power tests at CERN

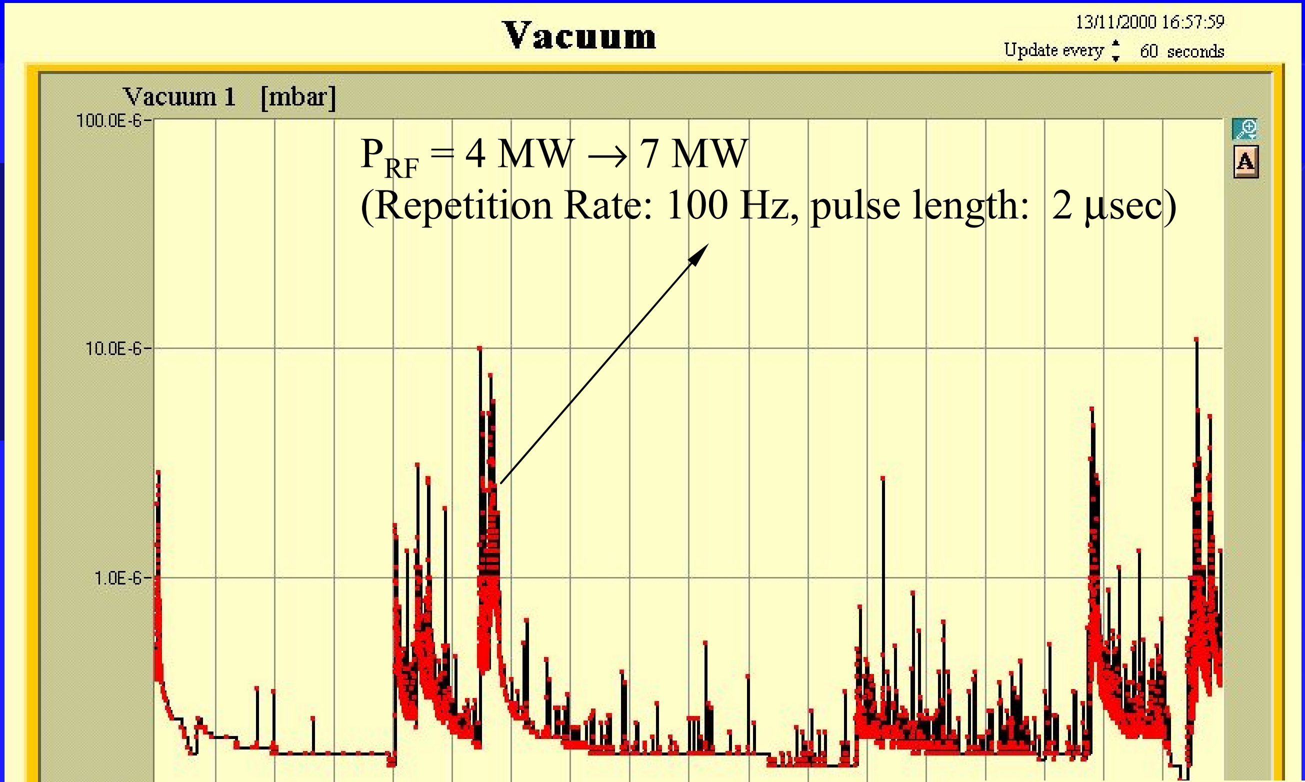


DAQ for RF power tests at CERN

Power tests:

RF conditioning story (CERN 2000)





Vacuum

13/11/2000 16:57:59

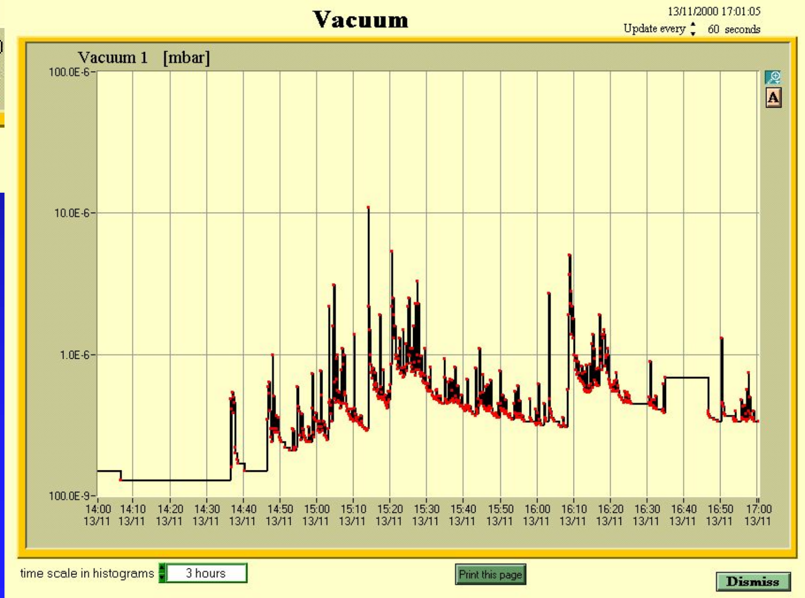
Update every 60 seconds

Vacuum 1 [mbar]

P_{RF} = 4 MW → 7 MW

(Repetition Rate: 100 Hz, pulse length: 2 µsec)

time scale in histograms 3days



Vacuum

13/11/2000 17:01:05

Update every 60 seconds

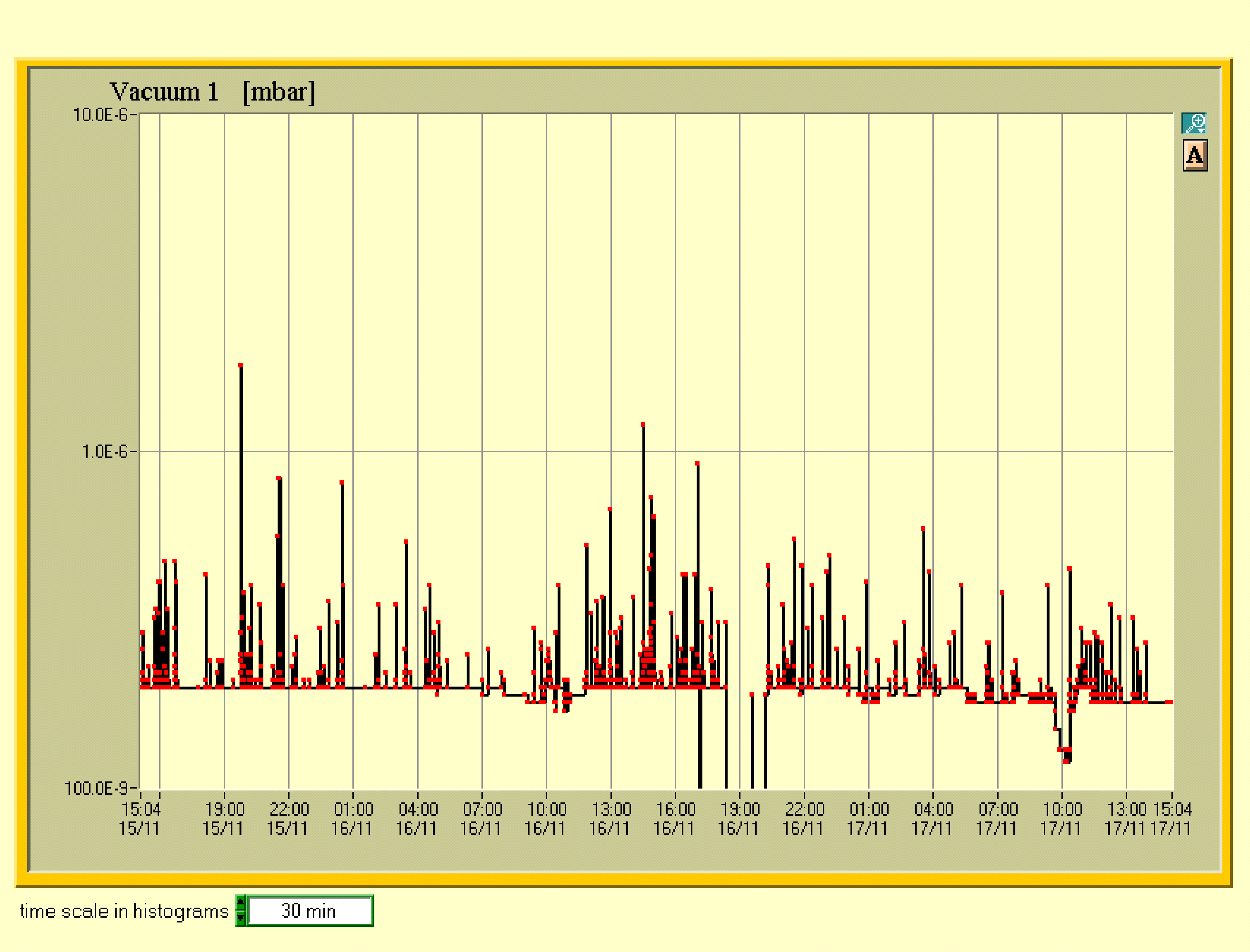
Vacuum 1 [mbar]

time scale in histograms 3 hours

RF power tests at CERN: multipactoring effect into LIBO when the RF power is injected

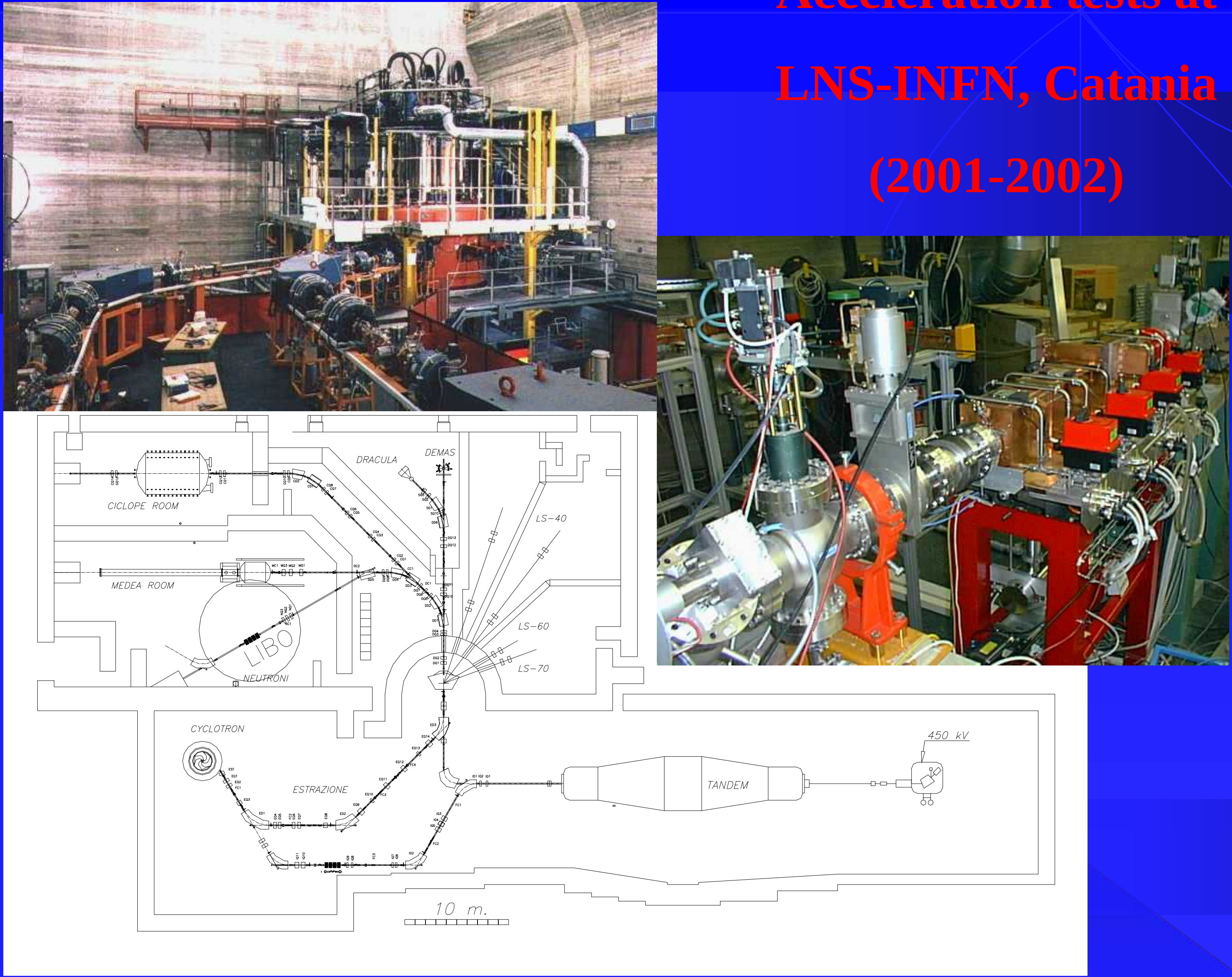
RF power tests (CERN):

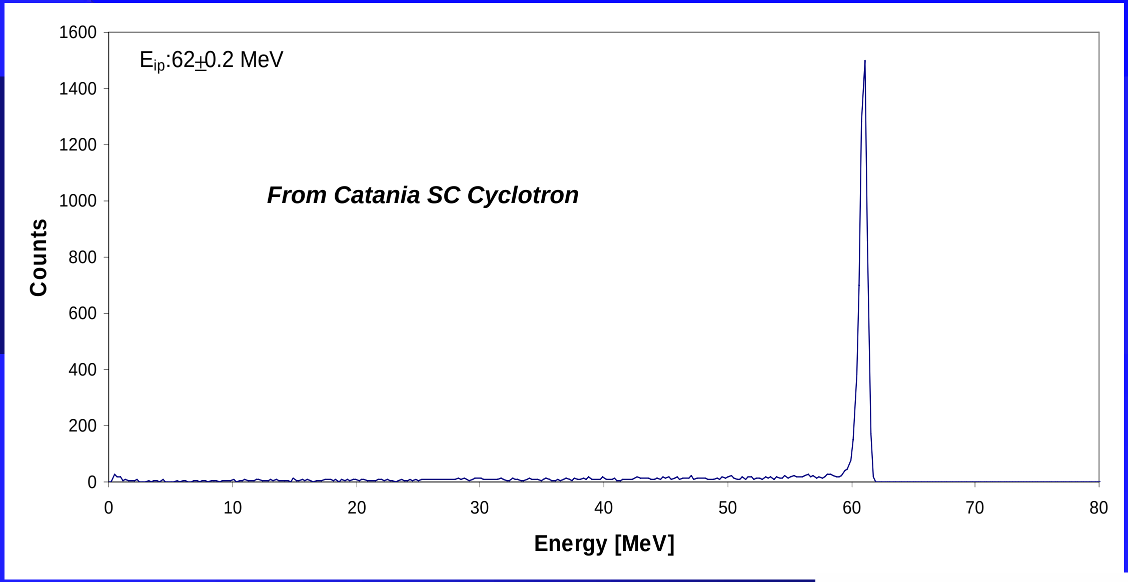
stable condition after RF conditioning



time scale in histograms 30 min

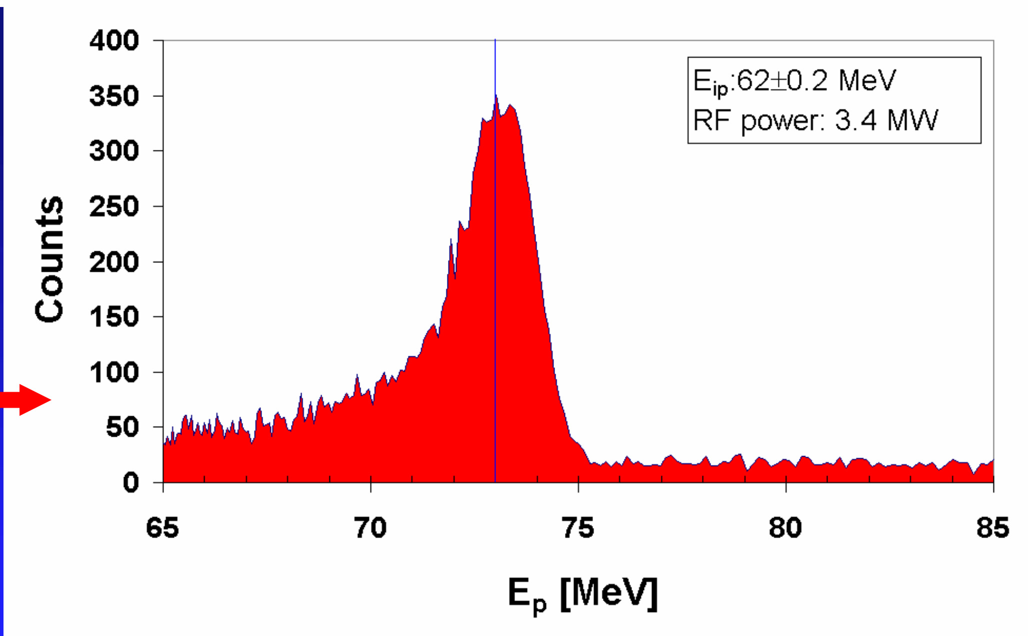
Acceleration tests at LNS-INFN, Catania (2001-2002)





- *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

Conclusion 1

- 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.

Conclusion 2

- 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.