COMMISSIONING OF THE LOW-ENERGY PART OF LINAC4

ALESSANDRA LOMBARDI
FOR THE COMMISSIONING TEAM
THE BIG PICTURE: LHC LUMINOSITY

\[ L = \frac{\gamma}{4\pi} \times f_r \times \frac{F}{\beta^*} \times n_b \times N_b \times \frac{N_b}{\epsilon_n} \]

- \( N_b \): number of particles per bunch
- \( n_b \): number of bunches
- \( f_r \): revolution frequency
- \( \beta^* \): normalised emittance
- \( \epsilon_n \): beta value at Ip
- \( F \): reduction factor due to crossing angle

From optics at Interaction point

From machine design and limitations (e-cloud)

Brightness from Injectors: defined at low energy

LHC INJECTOR CHAIN:

- **Linac2 (50 MeV)** 1978 length 40 m
  - 160mA, 100 μsec, 1 Hz
  - Max Space Charge Tune Shift reached
  - Injectors: defined at low energy

- **PS Booster (1.4 GeV)** 1972 – radius 25 m
  - 4 rings stacked
  - Output energy already upgraded twice

- **PS (25 GeV)** 1959 – radius 100 m

- **SPS (450 GeV)** - 1976 radius 1100 m

9/2/2014

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## PRESENT AND EXPECTATION

<table>
<thead>
<tr>
<th>LINAC2</th>
<th>LINAC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>Charge exchange injection (reduce emittance)</td>
</tr>
<tr>
<td>160mA</td>
<td>Lower current means better beam quality</td>
</tr>
<tr>
<td>50 MeV</td>
<td>Space charge tune shift at PSB injection is half</td>
</tr>
<tr>
<td>$1,\pi \text{ mm mrad}$</td>
<td>Smaller emittance</td>
</tr>
<tr>
<td>100 $\mu$sec $1\text{Hz}$</td>
<td>Longer injection in the PSB (100turns)</td>
</tr>
<tr>
<td>200 MHz / 40 m</td>
<td>RF frequency that is not widespread anymore. No components “off the shelf”.</td>
</tr>
<tr>
<td>Since 1978</td>
<td>Tanks, vacuum, mechanics are aging.</td>
</tr>
<tr>
<td>No longitudinal matching at injection</td>
<td>30-50% of the beam lost at injection</td>
</tr>
</tbody>
</table>

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LINAC4 machine layout - 352MHz

<table>
<thead>
<tr>
<th>Π-mode</th>
<th>CCDTL</th>
<th>DTL</th>
<th>Pre-injector</th>
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<tbody>
<tr>
<td>160 MeV</td>
<td>100 MeV</td>
<td>50 MeV</td>
<td>3 MeV</td>
</tr>
<tr>
<td>23 m 12 Modules</td>
<td>25 m 7 Modules</td>
<td>19 m 3 Tanks</td>
<td>9 m Source(s)</td>
</tr>
<tr>
<td>8 Klystrons: 12MW</td>
<td>7 Klystrons: 7 MW</td>
<td>3 Klystrons: 5 MW</td>
<td>2 solenoids</td>
</tr>
<tr>
<td>12 EMQ</td>
<td>7 EMQ + 14 PMQ</td>
<td>1 EMQ</td>
<td>11 EMQ</td>
</tr>
<tr>
<td>12 steerer</td>
<td>7 steerers</td>
<td>114 PMQ</td>
<td>3 Cavities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 steerers</td>
<td>2 Chopper units</td>
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**Commissioning stages**

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<thead>
<tr>
<th>160 MeV</th>
<th>105 MeV</th>
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<th>12 MeV</th>
<th>3 MeV</th>
<th>45 keV</th>
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<td>End 2015</td>
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<td>Chopping demonstrated</td>
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beam
### Commissioning stages

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- **Π-mode**
  - 160 MeV: 23 m, 12 Modules, 8 Klystrons: 12MW, 12 EMQ, 12 steerer
  - 100 MeV: 25 m, 7 Modules, 7 Klystrons: 7 MW, 7 EMQ + 14 PMQ, 7 steerers
  - 50 MeV: 19 m, 3 Tanks, 3 Klystrons: 5 MW, 1 EMQ, 114 PMQ, 2 steerers
  - 3 MeV: 9 m, Source(s), 2 solenoids, RFQ, 11 EMQ, 3 Cavities, 2 Chopper units

- **Beam**: ~76 m
MEASUREMENTS AT 45 KEV

1- take measurements varying solenoidal field and generate in tracking code

2 – back-trace to source out

3 - Result: we have an empirical input beam distribution that very well represents the dynamics in the LEBT and the rest of the accelerator (remember HB2010)
AT THE RFQ INPUT PLANE

Comparison of measured emittance (yellow) and RFQ acceptance (pink). The expected transmission thru the RFQ is 75%. (PARMTEQ + TOUTATIS)

Measured current: 16mA for 200μsec.
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Comparison of measured emittance (yellow) and RFQ acceptance (pink). The expected transmission thru the RFQ is 75%. (PARMTEQ + TOUTATIS)

Measured current: 16mA for 200μsec.

This is NOT the final source!!!
FIRST BEAM THRU THE RFQ

Wednesday 13/03/13 at 16h10
10mA H- accelerated to 3 MeV
AT 3 MEV : 4 BURNING QUESTIONS

• Does the RFQ work?

• Does the chopper chop?

• If yes, does it degrade the emittance of the thru beam?

• Can the beam be matched to the DTL (permanent magnet, not much flexibility....)?
1-RFQ TRANSMISSION

RFQ Transmission vs. RF power for different pressure in the LEBT (neutralisation). The nominal RFQ power is 400 kW.

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2-“CHOPPING”
REMOVING MICROBUNCHES (150/352) TO ADAPT THE 352MHZ LINAC BUNCHES TO THE 1 MHZ BOOSTER FREQUENCY

Match from the RFQ

Chop

Match to the DTL
2-“CHOPPING”

REMOVING MICROBUNCHES (150/352) TO ADAPT THE 352MHZ LINAC BUNCHES TO THE 1 MHZ BOOSTER FREQUENCY
CHOPPER DEVICE

- Meander line on ceramic board
- Housed in a quadrupole
- 700 Volts
- Rise/fall time: 2nsec
2-BEAM CHOPPING

At the BCT after the inline dump

At the wire scanner before the dump

Measured Current in BCT04040 (mA) vs L4L.QFC03130

Simu 2008

Meas 2014
Emittance measured with chopper off (left) and with chopper on (right) downstream the inline dump.
simulation codes (TraceWin and Travel) predict 95% transmission thru the DTL for the measured beam.
4-MATCHING TO THE DTL

Simulation codes (TraceWin and Travel) predict 95% transmission thru the DTL for the measured beam.
FROM 3 TO 12 MEV

August 6th, 7.5 mA going in, 7.5 mA accelerated

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SO FAR …..

- Acceleration 45 keV to 12 MeV is validated
  - RFQ holds the voltage, accelerates and responds to changes in RF power
  - The chopper chops
  - DTL tank1 accelerates the beam without losses
EMITTANCE, ENERGY SPREAD, ETC ETC

- **Longitudinal emittance** is rms normalised
  - pi deg MeV
  - Deg at 352MHz

- **Transverse emittance** is rms normalised
  - pi mm mrad
  - Target value is 0.4
THE MEASUREMENT BENCH

Spectrometer Grid
Bunch Shape Monitor
Slit and Grid Emittance
Laser + Diamond

BCT
28 Deg bend
Quadrupoles
Slits 0.4 mm and LASER
Bunch Shape Monitor

Emittance Metre Grids

Beam
RMS NORMALISED TRANSVERSE EMITTANCE AT 3 MEV SEEMS TO BE 0.3 PI MM MRAD
RMS NORMALISED TRANSVERSE EMITTANCE AT 3 MEV SEEMS TO BE 0.3 PI MM MRAD
RMS NORMALISED TRANSVERSE EMITTANCE AT 12 MEV SEEMS TO BE WHAT WE EXPECT

Slit-and-grid (yellow) compared to expectation (pink)

<table>
<thead>
<tr>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
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Emitt rms normalised = 0.35 π mm mrad
LONG EMITTANCE AT 3MEV-INDIRECT

Reconstruction

BU.1 fixed

BU.2 varying

BU.3 OFF

Measurement

BSM

RFQ

Bunch Shape Monitor
LONG EMITTANCE AT 3MEV-INDIRECT

Beam RMS phase vs Cavity amplitude

- Measurements
- Simulation
- Reconstructed

Reconstruction

Measurement

Bunch Shape Monitor

RFQ

BU.1 fixed

BU.2 varying

BU.3 OFF

BSM
LONG EMITTANCE AT 3MEV-INDIRECT

VISIT
THPP033/TUPP100
MOPP025
LONG EMITTANCE AT 3 MEV - INDIRECT

Energy spread
Expected from simu : 21 keV
Measured from phase : 22 keV
Spectrometre : 19 keV

Measured from phase profiles
Alpha=0.2
Beta = 380. deg/MeV
Emitt = 0.16 deg MeV

Expected from simulations:
Alpha= 0.0
Beta = 400 deg/MeV
Emitt = 0.19 deg MeV
SPECTROMETRE - AT 12 MEV

rms energy spread: 49.2 keV (simulations)

rms energy spread: 52.8 keV (measured)
SO FAR....

Acceleration 45 keV to 12 MeV is validated

Emittance Measurements confirm that the beam behaves according to code predictions. (PARMTEQ, PATH, TRACEWIN)

Reconstruction technique and diagnostic performance are validated!

Reconstruction is based on:

1) Finding first guess with conventional matrix inversion.
2) Fine tuning the guess by forward tracking and best fitting the measurement’s data
LESSTONS LEARNT

1) A 10 Watt beam (10mA, 3MeV, 300 μsec, 1Hz) can drill a hole through a bellow

2) Diagnostics devices can multitask

3) Effect of RF defocusing is measurable at 3 MeV!

4) DTL tank1 can act as a longitudinal monitor
MISTAKES MADE AND LESSONS LEARNT

1) A 10 Watt beam (10mA, 3MeV, 300 μsec, 1Hz) can drill a hole through a bellow

2) Diagnostics devices can multitask

3) Effect of RF defocusing is measurable at 3 MeV!

4) DTL tank1 can act as a longitudinal monitor

VISIT THPP033 and TUPP038
On December 12 at 16:30 a severe vacuum leak was observed in the MEBT line. It was located on the bellow downstream the first buncher cavity, on the left side when looking down the beam line.

A severe misalignment between the RFQ and the MEBT that was not present at the 3 MeV test stand and was later confirmed by survey.

An optic that favoured amplification of this misalignment whilst focusing the beam to sub mm size in the other direction.

A phase advance such that the loss occurred on the “wave” (or lip) of the bellow which is only 200 microns thick and it is an aperture limitation (25.1 mm vs 28 mm of adjacent vacuum chamber).
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Transmission through DTL tank1

- Green triangles: meas-Bunchers_off
- Blue diamonds: meas-Bunchers_on
- Purple crosses: simu-Bunchers_off
- Red squares: simu-Buncher_on

Phase of DTL tank1 - degrees at 352 MHZ

Bunchers on

Bunchers off

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SUMMARY

• The LINAC4 has been commissioned up to 12 MeV with a temporary source. Only 148 MeV to go! (3 commissioning stages over 6 are done)

• The agreement between measurement and simulations is very good, thanks to the time we have dedicated to generate a distribution from measurements at the low energy end – HB2010. Simulation have been our guide and give us a hint of where to look in case of problems (e.g. alignment issues)

• We have validated transverse and longitudinal emittance reconstruction methods which will be extensively used for the next stages of commissioning

• We have not yet experienced full space charge effects, which will come with the new source.
VISIT THESE POSTERS!

- On longitudinal measurements: MOPP025
- On transverse measurements and reconstruction: THPP033/TUPP100 and TUPP038
- On the source: TUPP036
- On laser-based emittance measurement: TUPP035
- On the Radio Frequency Quadrupole: THPP037
- On the DTL: TUPP089, SUPG018, THPP036, THPP0
- On LLRF: THPP027