Linac4 chopper line commissioning strategy

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Abstract

The report outlines the strategy for beam-based commissioning of the Linac4 3 MeV chopper line as currently scheduled to start in the second half of 2011 in the Test Stand Area. A dedicated temporary diagnostics test bench will complement the measurement devices foreseen for permanent installation in the chopper line. A commissioning procedure is set out as a series of consecutive phases, each one supposed to meet a well-defined milestone in the path to fully characterise the beam-line. Specific set-ups for each stage are defined in terms of beam characteristics, machine settings and diagnostics used. Operational guidelines are given and expected results at the relative points of measurements are shown for simulated scenarios (on the basis of multi-particle tracking studies carried out with the codes PATH and TRACEWin). These are then interpreted in the light of the resolution limits of the available diagnostics instruments to assess the precision reach on individual measurements and the feasibility of techniques aimed at finding working points via particular signatures and signal variations. Where possible different techniques are compared for cross-validation. An attempt is also made to define a time schedule in terms of the number of shifts necessary to accomplish each phase, the baseline assumption being of a single 8hrs shift per day with two main commissioners on duty and dedicated support for all essential systems (diagnostics, RF, power, controls, vacuum, source experts etc.). A 50% allowance for general machine unavailability has been assumed. All hardware commissioning and cold check-out tests are outside the scope of this note and are assumed to have already been completed by the start time of beam commissioning.
INTRODUCTION

This document outlines the strategy for beam-based commissioning of the 3MeV Linac4 chopper line in the Test Stand area. According to the latest planning schedule, Test Stand operation will take place from January 2011 to the third quarter of 2012, for a total of >360 working days, to be shared between source optimization, RFQ and MEBT commissioning. As a baseline, it is here assumed that work will be organized in one daily shift of 8hrs length, preceded by some time (~2hrs) to be dedicated to source tuning and beam stabilization, when needed. Rota should be organized to have two main commissioners available per shift along with dedicated support for all essential systems (diagnostics, RF, power, controls, vacuum, source experts etc.). A description of the measurements strategy to be followed is given in this document, together with an estimate of the time schedule. A 50% allowance for general machine unavailability has been built and accounted for on top of the numbers given. Likewise, all hardware commissioning and cold check-out tests are outside the scope of this note and are assumed to have already been completed by the start time of beam commissioning.

DIAGNOSTICS

The available diagnostics suite for beam measurements and characterization includes the devices permanently installed in the MEBT line (two transformers, two slow wire scanners and two clamp-on steerers (Fig.1) and the instrumentation foreseen on the 3MeV movable diagnostics test bench, illustrated in Fig.2 and described in detail in note [1].

Figure 1 Mechanical drawing of the chopper line with the elements of diagnostics highlighted (top) and schematic layout (bottom) with magnets and buncher cavities (in green). The chopper plates are housed inside the central quadrupoles L4L.QDB3090 and L4L.QDB3110.

The complete list of diagnostics devices available is given in Table 1, together with some specifications in terms of resolution and operational capabilities. These should allow a complete characterization of the beam in all planes via the following measurements:
Table 1 List of instrumentation devices available for the chopper line commissioning with relative specifications.

<table>
<thead>
<tr>
<th>System</th>
<th>Max current</th>
<th>Max rep rate [Hz]</th>
<th>Time resolution</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEBT Slow Wire scanners</td>
<td>80mA</td>
<td>2</td>
<td>Over several pulses</td>
<td>0.1mm</td>
</tr>
<tr>
<td>BCMs</td>
<td>80mA</td>
<td>2</td>
<td>1µs</td>
<td>0.5 mA</td>
</tr>
<tr>
<td>BPMs</td>
<td>80mA</td>
<td>2</td>
<td>10µs</td>
<td>0.1mm-1deg</td>
</tr>
<tr>
<td>Emittance meter</td>
<td>80mA</td>
<td>2</td>
<td>100kHz</td>
<td>0.1 mm mrad (SEM)</td>
</tr>
<tr>
<td>Spectrometer</td>
<td>80mA</td>
<td>2</td>
<td>100kHz</td>
<td>&lt;20keV/mm</td>
</tr>
<tr>
<td>Bunch shape monitor</td>
<td>80mA</td>
<td>2</td>
<td>100kHz</td>
<td>1 deg</td>
</tr>
<tr>
<td>Halo monitor</td>
<td>80mA</td>
<td>2</td>
<td>1ns</td>
<td>2mm,10^5 dyn range</td>
</tr>
</tbody>
</table>

The main beam parameters for the commissioning scenarios are given in Table 2. A lower current beam (I=7mA), or “pencil beam”, produced by insertion of a 10mm circular aperture iris in the LEBT [2], will also be used at certain stages of commissioning for dedicated measurements like structure alignment, acceptance scans etc (while reducing radiation levels and the impact of beam losses on the structures).

**REFERENCE BEAM DYNAMICS**

The nominal beam dynamics behaviour through the MEBT for the unchopped beam case (chopper plates switched off) is summarised for reference in Figs.3-5, for the case of an initial beam distribution of 50k particles and 65mA peak current tracked through the RFQ. Figure 3 shows the horizontal and vertical beam envelopes from the RFQ exit through the MEBT and test bench, whereas Fig.4 shows the evolution in the energy spread and longitudinal phase width. Fig. 5 shows the transverse and longitudinal emittance growth. In all plots s=0 corresponds to the RFQ output/MEBT input plane. The gradients of the last four quadrupoles have been changed from their nominal baseline values - used for matching to the DTL Tank1 - and retuned to obtain a parallel beam behaviour at the MEBT output (in order to minimise losses along the diagnostics bench where no transverse focusing is foreseen).
Table 2 Commissioning beam characteristics at the output of the RFQ.

<table>
<thead>
<tr>
<th></th>
<th>Commissioning (full)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length</td>
<td>50-100\mu s</td>
</tr>
<tr>
<td>Rep rate</td>
<td>1Hz</td>
</tr>
<tr>
<td>Max beam current</td>
<td>65mA</td>
</tr>
<tr>
<td>Average beam current (after chopping)</td>
<td>40 mA</td>
</tr>
<tr>
<td>Beam energy</td>
<td>3MeV</td>
</tr>
<tr>
<td>Transverse beam emittances at structure output planes (RMS norm)</td>
<td>0.25 mm mrad</td>
</tr>
<tr>
<td>Longitudinal emittances</td>
<td>0.13 deg MeV (at 352MHz)</td>
</tr>
</tbody>
</table>

Also the voltage on the last buncher cavity will be adapted during commissioning to reduce the longitudinal focusing of the beam and allow measurements at devices located a few metres downstream, where the beam would otherwise be almost completely debunched. Settings for the two schemes are summarised in Table 3.
Table 3 Last MEBT FODO quadrupole settings and output beam Twiss parameters for the nominal case (beam matched to DTL) and commissioning case (beam matched to diagnostics test bench).

<table>
<thead>
<tr>
<th>Quadrupole</th>
<th>Nominal [T/m]</th>
<th>Commiss. [T/m]</th>
<th>Nominal alpha x</th>
<th>Commis. alpha x</th>
<th>Nominal Beta x</th>
<th>Commis. Beta x</th>
<th>Nominal Alpha y</th>
<th>Commis. Alpha y</th>
<th>Nominal Beta y</th>
<th>Commis. Beta y</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4L.QDD3170</td>
<td>10.80</td>
<td>8.14</td>
<td>5.5</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4L.QFD3180</td>
<td>-8.00</td>
<td>-6.3</td>
<td>0.86 m/rad</td>
<td>2.2 m/rad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4L.QDA3200</td>
<td>24.52</td>
<td>20.8</td>
<td>-0.67</td>
<td>-0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4L.QDA3220</td>
<td>-28.31</td>
<td>-16.2</td>
<td>0.29 m/rad</td>
<td>1.3 m/rad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 5RMS horizontal and vertical beam envelopes through MEBT and test bench.
Figure 4 Longitudinal phase width and energy spread evolution (MEBT + test bench).

Figure 5 Normalised RMS beam emittances in the longitudinal and transverse planes.
COMMISSIONING STRATEGY

Three different modular configurations of the test bench will be used, for the sequential commissioning of the RFQ, MEBT and DTL Tank1, as shown in Fig.6. The diagnostics line is to be mounted on a support that should be capable of moving as a rigid unity in order to facilitate the change from one configuration to the other. The RFQ and DTL Tank1 measurements strategy (top and bottom layouts respectively in Fig.6) will be detailed in separate notes, the present one focusing only on the MEBT.

Commissioning of the Linac4 chopper line will involve steering and orbit correction, quadrupole tuning, RF amplitude and phase scans, and beam matching in both transverse and longitudinal planes. This document details a strategy of measurements to be carried out to establish the MEBT settings, in the second one of the installations illustrated in Fig.6. At this stage of commissioning it is assumed that the RFQ will have already been tuned and hence that the beam at the entrance of the MEBT will meet nominal specifications.

Several stages of commissioning have been identified, in the following order:

**STAGE 0:**

**Aim:** Ensure beam transport through MEBT and test stand, preliminary quadrupole tuning with a response matrix technique, orbit correction with steerer magnets.

**Setup:** MEBT+test bench – Pencil beam at 1Hz rep rate, 50-100 μs pulse length, bunchers off, chopper plates ON for response matrix measurements, when needed.
Planned schedule:

<table>
<thead>
<tr>
<th>Tasks</th>
<th>shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 Observe beam on BPMs, WS, measure transmission</td>
<td>3</td>
</tr>
<tr>
<td>0.2 Initial quadrupole tuning via response matrix technique – measure calibration constants (4 quad types), confirm polarities, measure beam offsets</td>
<td>8</td>
</tr>
<tr>
<td>0.3 Orbit steering and initial aperture scan</td>
<td>3</td>
</tr>
</tbody>
</table>

Procedure: Observe beam position signals on BPMs and wire scanners, measure transmission at BCTs. Derive quadrupole response matrices, measure calibration constants for the four quadrupole types, check polarities. Measure beam offsets and perform orbit steering and initial aperture scans.

<table>
<thead>
<tr>
<th>Quadrupole</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4L.QDA03010;</td>
<td>type III</td>
</tr>
<tr>
<td>L4L.QDA03030;</td>
<td>type III</td>
</tr>
<tr>
<td>L4L.QFA03050;</td>
<td>type III</td>
</tr>
<tr>
<td>L4L.QDB03090;</td>
<td>type VII</td>
</tr>
<tr>
<td>L4L.QDA03200;</td>
<td>type III</td>
</tr>
<tr>
<td>L4L.QDB03110;</td>
<td>type VII</td>
</tr>
</tbody>
</table>

Table 4 List of quadrupole magnet types installed on the MEBT.

Four different magnet families are used in the MEBT, as listed in Table 4. During commissioning, a quadrupole response matrix scan will be performed for at least one magnet of each type, for beam-based measurement of the calibration constants and beam offsets. For the type III magnets, the beam will be kicked with the first steerer of the MEBT, while scanning over the currents applied to L4L.QFA3030, to observe the beam deviation at the first wire scanner. For types VII and IX the chopper plates would be used to deflect the beam at the entrance of L4L.QDB3110 and L4L.QFC3130 and the beam centroid offset would then be measured on the second wire scanner, near the chopper dump. For Type IV magnets the beam will be kicked with the second steerer and its off-center deviation measured on the first BPM of the diagnostics test bench. Measurement of the offsets is relative to the trajectory passing through the centres of the magnets (alignment errors are not considered). Figure 7 shows an example of response matrix measurements for quadrupole L4L.QDD3170 and L4L.QDB3110: the vertical position of the beam centroid at the downstream wire scanner location is plotted as a function of the steerer kick applied to the beam entering the quadrupole for different field gradients, varying between ±20% of the nominal setting. By measuring the beam position while scanning over the quadrupole field, it will be possible to perform an initial quadrupole tuning and determine the beam offsets at the quadrupoles for input to orbit correction studies. For the bottom case, applying a chopper voltage of 250V will allow to measure the gradient with a precision of ±10% (assuming a 0.1mm resolution of the BPM). For the top case, applying a 5mrad kick with the steerer should allow to tune the gradient to a ±5% precision with a resolution of ~0.2mm on the wire scanner.
Figure 7 Example of quadrupole response matrix measurement (type IV and VII magnets).

Figure 8 Example of orbit steering: before correction (red line), after one iteration of steering algorithm (green line) and two iterations (blue)

The beam offsets thus derived and those measured at the wire scanners will give an input to orbit correction studies. Figure 8 shows an example of beam steering for an error study case with initial 75% transmission. The red curve gives the horizontal centroid beam offset before correction, and
the green and blue curves show the same offset after one and two iterations respectively of the steering algorithm. A 95% transmission is recovered with <2mT/m gradient applied on the two steering magnets. To be achieved at the end of this stage: preliminary quadrupole settings and first orbit corrections.

**STAGE1:**

**Aim:** characterize buncher cavities, set RF phase and amplitude points, measure average beam energy and energy spread.

**Setup:** MEBT+test bench, pencil beam, 1Hz rep rate, 50-100μs pulse length, chopper plates OFF.

**Planned schedule:**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Calibrate bunchers on spectrometer line (scan phases and amplitudes with spectro quads off)</td>
<td>5</td>
</tr>
<tr>
<td>1.2 Cross-check with inline TOF measurements, beam-based PU calibration and resolution</td>
<td>5</td>
</tr>
<tr>
<td>1.3 Cross-check with bunch profile measurements at the Feshenko monitor (phase spread vs buncher settings)</td>
<td>5</td>
</tr>
<tr>
<td>1.4 Transmission vs buncher on/off</td>
<td>1</td>
</tr>
<tr>
<td>1.5 Measure energy spread on spectrometer</td>
<td>1</td>
</tr>
</tbody>
</table>

**Procedure:**

1) A first buncher calibration will be done on the spectrometer line (with the quadrupoles switched off), in the following steps:

- Buncher 1 calibration – buncher 2,3 off
- Buncher 2 calibration – buncher 3 off, buncher1 at nominal values
- Buncher 3 calibration – bunchers 1,2 at nominal values
Figure 9 MEBT buncher cavities RF characterisation with the method described above. Resolution is approximately 0.6mm beam centroid displacement per degree offset in phase and 0.2mm displacement per kV offset in voltage amplitude.
Set RF phase point:
Set maximum voltage on the cavity and spectrometer Bfield corresponding to 3MeV and measure beam displacement on screen while scanning over phase values. A correct value of ±90 deg is reached when the beam is centered. Sign ambiguity in the phase value can be solved from the sign of the derivative of the curves (beam centroid vs phase offsets).

Set RF amplitude point:
Set RF buncher phase to 0deg in order to have an output beam energy of 
\[ W = W_0 + V_{\text{max}} \cos \varphi = W_0 + V_{\text{max}} \]
If the spectrometer field is set to correspond to an energy W, then the beam will appear centered on the SEM grid at the end of the spectrometer line. Similarly beam centroid displacement can be measured while scanning over voltage values. The energy and the maximum effective voltage at 0 deg phase are linear functions of the magnet field required to re-center the beam, as shown in Fig. 9, according to:
\[ \Delta W / W_0 = 2 \Delta x / \alpha L = \beta^2 \gamma / (\gamma - 1) \rho \Delta B / B, \]
where \( \Delta x \) is the beam displacement, \( \alpha \) the bending angle of the magnet and \( L \) the length of the spectrometer line [3].

Figure 9 shows the results for the phase and voltage scans of the buncher cavities for the three cases described above with nominal parameters. From the linear fits to the curves one can deduce that a 0.2mm resolution in the measurement of beam centroid displacement would allow to set the cavities phase with a precision of ±0.5 degrees and the cavities voltage with a precision of ±1kV. In fact the expected resolution of the SEM grid should be even better (of the order of 50μm),

**Figure 10 Beam distributions in the longitudinal plane for a nominal beam at the locations of the pick-ups on the test bench (bunchers at nominal amplitude settings).**
Figure 11 Beam distributions in the longitudinal plane for a nominal beam at the locations of the pick-ups on the test bench (voltage on the third buncher cavity has been reduced to 100kV).

which should allow measuring voltage deviations with the precision of ±0.25kV.

2) A crosscheck of the settings found in 1) should be done with TOF measurement of the output average beam energy using the BPMs installed on the test bench. This will also provide a means of beam-based commissioning of the devices (phase/position readings, phase resolution, noise).

Pick-ups are foreseen to be installed on the inline part of the test bench at the following locations (where s=0 corresponds to the RFQ output plane):

- PU1 at s=4318.2mm
- PU2 at s=5148.2mm
- PU3 at s=6275.2mm

with distances between them: L12=830mm, L23=1127mm, L23=1957mm. The analytical calculation of TOF resolution for two scenarios of BPM measurement accuracies (in phase and position) gives:

<table>
<thead>
<tr>
<th>PUs</th>
<th>Case1 [keV]</th>
<th>Case2 [keV]</th>
<th>3 MeV</th>
<th>12 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>3.50</td>
<td>2.57</td>
<td>1-2</td>
<td>23.8</td>
</tr>
<tr>
<td>1-3</td>
<td>1.48</td>
<td>1.09</td>
<td>1-3</td>
<td>10.1</td>
</tr>
<tr>
<td>2-3</td>
<td>2.58</td>
<td>1.90</td>
<td>2-3</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.4</td>
</tr>
</tbody>
</table>
for the cases defined by the following assumptions on the diagnostics resolution:

1) \( d\phi = 2\,\text{deg}, dL=0 \)
2) \( d\phi = 1\,\text{deg}, dL=0.3\,\text{mm} \)

Calculations show that a 1\% sensitivity on the average energy measurement should be within reach. According to the curves in Fig.9 (secondary energy axis), this should translate into a precision of ±3 keV and ±1 deg respectively in the setting of the amplitude and phase points of the RF bunchers.

Figure 10 shows the nominal beam distributions in the longitudinal plane at the pick-ups positions on the test bench. For nominal settings the beam arrives at PU3 almost completely debunched. Reducing the voltage applied to the third buncher cavity in the MEBT slows down the debunching process, as is shown in Fig.11. Fig. 12 shows the beam debunching evolution at the three pick-up positions for several input current values and different buncher focusing schemes.

3) As further crosscheck of the buncher settings and longitudinal plane characterization, bunch profiles should be measured with the Feshenko monitor (on a low current beam, with chopper plates unpowered and slit withdrawn) while varying buncher settings. Fig.13 shows (on the left) a plot of the Gaussian fitted RMS bunch phase widths as a function of the buncher voltages (normalized to their nominal settings); to the right is a plot of the bunch profiles at the Feshenko monitor.
location on the test bench when varying the voltage on L4L.BUN3040 by ±10% (corresponding to \( \sigma = 26, 30 \) and 35 degrees). The ±1deg resolution in phase measurement of the instrument should allow to derive the buncher voltages with a precision of a few %.

![Figure 13](image)

**Figure 13** Variation in the bunch phase widths (measured at the location of the Feshenko monitor) as a function of MEBT buncher voltages (left). To the right, simulated longitudinal bunch profiles at the Feshenko monitor location, when changing the voltage on L4L.BUN3040 by ±10% (fitted Gaussian \( \sigma = 26, 30, 35 \) deg).

**Milestone:** by the end of Stage1, the setting up of the buncher cavities’ RF phase and amplitude points should be accomplished.

**STAGE 2:**

**Aim:** establish transverse matching conditions, find initial Twiss parameters, perform quadrupole fine tuning.

**Setup:** MEBT + test bench. Full current beam, 1Hz rep rate, 50-100 ms pulse length, chopper plates OFF.

**Planned schedule:**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Quadrupole gradients scan – measure transmission, emittances, profiles (with offline analysis if no clear signatures)</td>
<td>10</td>
</tr>
<tr>
<td>2.2 Online model matching of RMS sizes at WS positions and test bench to solve for input beam Twiss parameters</td>
<td>8</td>
</tr>
<tr>
<td>2.3 Aperture scan on low current beam</td>
<td>3</td>
</tr>
</tbody>
</table>
**Procedure:** quadrupole gradients scan technique with measurement of beam profiles on wire scanners, transmission on transformers and emittances on test bench scanner.

A quadrupole scanning technique often seen in literature [4] as method for tuning consists in studying the variation in several beam parameters (measured at the location of the corresponding diagnostics devices) while changing quadrupole gradients within a ±20% range from their nominal settings. Only one quadrupole gradient is changed at a time. The results represent however a fairly idealized case: no mismatch or errors are assumed in the simulations, and while scanning over one quadrupole, the others are assumed to be at their nominal settings. The technique can hence be reliably applied only for fine tuning of the quadrupoles, when already close to the theoretical solution. Here we assume that quadrupole response matrix measurements (as described in Fig.7) should have already provided an initial rough tuning. Studies have been carried out grouping the quadrupoles in three sections:

A) RFQ to MEBT (first FODO: L4L.QDA3010, L4L.QFA3030, L4L.QDA3050, L4L.QFA3070);  
B) MEBT central quads (L4L.QDB3090, L4L.QDB3110, L4L.QFC3130);  
C) MEBT to DTL (last FODO: L4L.QDD3170, L4L.QFD3180, L4L.QDA3200, L4L.QDA3220).

Fig.14 shows results for this scanning technique applied to the first group of quadrupoles in A). Beam parameters (size, emittance, intensity) are measured at several diagnostics locations while varying quadrupole gradients.

Beam current readings from the transformers provide the best signature to tune the quadrupoles (maximum in transmission in correspondence of the nominal values). The wire scanners and transformers on the chopper line are referred to as #1 and #2 according to their longitudinal position in the order seen by the beam.

Fig.16 shows the same curves for the central quadrupoles gradient scan (group B) in the list above) over a ±20% range. Good signatures for tuning L4L.QDB3110 and L4L.QFC3130 also come from local maxima in the beam transmission.

Fig.15 and 17 show the variations in the output beam Twiss parameters as measured at the emittance meter (slit) position when scanning the quadrupole gradients. Some of the maxima and minima are located in the vicinity of the nominal settings and could then help provide signatures for tuning.

Finally, for the last 4 quadrupoles in the chopper line (L4L.QDD3170, L4L.QFD3180, L4L.QDA3200, L4L.QDA3220), no such clear discriminating clues are at hand from observing beam parameters at the test bench diagnostics devices in the MEBT+bench configuration (second in Fig.6), due to the close proximity of the observation points to the quadrupoles being tuned. Better signatures can be obtained by measuring beam parameters at the exit of DTL tank1 while varying the quadrupole gradients of the last F0D0 in the chopper line (see Fig.18), with the diagnostics bench installed according to the third scheme in Fig.6. In this case the tuning study will also provide direct evidence of the quality of beam matching between the two structures. Good minima signatures can be distinguished for L4L.QDA3200 (q10 in the pictures); the available diagnostics resolution might however be a limit to an efficient value discrimination.
Figure 14 Beam parameters variation at the MEBT wire scanners and diagnostics test bench as a function of quadrupole gradients scan in the first MEBT F0D0 (-20%:+20%). q1= L4L.QDA3010, q2=L4L.QFA3030, q3=L4L.QDA3050, q4=L4L.QFA3070.
Figure 15 Twiss parameters variation at the emittance meter as a function of quadrupole gradients scan in the first MEBT F0D0 (-20%:+20%). \( q_1 = L4L.QDA3010, q_2 = L4L.QFA3030, \)
\( q_3 = L4L.QDA3050, q_4 = L4L.QFA3070. \)
Figure 16 Results for the central quads (q5=L4L.QDB3090, q6=L4L.QDB3110, q7=L4L.QFC3130) gradient scan. Beam is measured at the MEBT wire scanners and test bench devices (MEBT+bench configuration).
Figure 17 Twiss parameters variation at the emittance meter as a function of quadrupole gradients scan of the MEBT central quadrupoles (q5=L4L.QDB3090, q6=L4L.QDB3110, q7=L4L.QFC3130).
In a different approach, the gradients of the same quadrupoles - L4L.QDD3170, L4L.QFD3180, L4L.QDA3200, L4L.QDA3220 – have all been varied at the same time using uniformly distributed random values within a ±20% range off their nominal settings.

The plots in Fig.19 show the distribution in the beam RMS horizontal emittance values at the end of DTL Tank1 as a function of the quadrupole gradients settings. The red square indicates the nominal configuration. Apart from L4L.QDA3200, where the local minimum gives a fairly clear signature for tuning, in all other cases there is no striking correlation to be seen in these one-dimensional plots and the profiles of the distributions are rather flat. However, combining information in a multi-variables type of approach allows to reduce the size of the parameter space scanned for tuning. Fig.20 shows (to the left) the correlation between RMS horizontal emittance and RMS beam size at the end of Tank1 for the statistical sample examined.

By applying a cut requiring the RMS horizontal and vertical emittances to be below 0.4 mm mrad and the transmission to be above 95%, one can reduce the data sample studied to 10% of its original size, and by plotting a histogram of the quadrupole gradients for the sample obtained (Fig.20 right) it is possible to come close to the nominal values (peak around 1) with a 10% statistical deviation.
Figure 19 Horizontal beam emittance distributions at the end of DTL Tank1 when all the last four F0D0 quadrupoles in the MEBT are randomly changed in gradient by up to ±20%.

Figure 20 Correlation between horizontal emittance and transverse beam size values on a test sample of MEBT lattices where the gradients of the last F0D0 quadrupoles have been changed by up to ±20% [left]. To the right is a histogram of one of the last F0D0 quadrupole gradients for a reduced data sample obtained after applying a cut in a multi-variables phase space of output beam characteristics at the end of DTL tank1.
A more straightforward and faster procedure for beam matching would be via an online model software application having live machine data input and an interface to simulation tracking codes in order to compare measured and model predicted beam sizes at several different locations along the MEBT and DTL Tank1 for a variety of MEBT quadrupole settings and solve for the beam entrance Twiss parameters by difference minimization. The implementation of such a tool is being studied at the moment [5].

**STAGE 3:**

**Aim:** full current beam characterization

**Setup:** MEBT+test bench, full current beam, 50-100μs pulse, 1Hz rep rate, chopper plates OFF.

**Planned schedule:**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Confirm RF settings for higher current beam</td>
<td>1</td>
</tr>
<tr>
<td>3.2 Measure output beam position &amp; transverse emittance : study variations within a pulse and pulse to pulse</td>
<td>3</td>
</tr>
<tr>
<td>3.3 Transverse beam halo studies and comparison with wire scanner measurements</td>
<td>2</td>
</tr>
<tr>
<td>3.4 Measure energy spread on spectrometer and bunch profile on Feschenko monitor: study variations within a pulse and pulse to pulse</td>
<td>3</td>
</tr>
<tr>
<td>3.5 Measure average energy and study stability during a pulse and pulse to pulse</td>
<td>3</td>
</tr>
</tbody>
</table>

**Procedure:**
Increase pulse length: measure beam loading, beam parameters variation within a pulse and pulse-to-pulse. Aperture scan. Energy spread measurements with spectrometer. Transverse beam halo studies and comparison with wire scanner measurements. Longitudinal halo studies (if dynamic range of electromultiplier gain allows to resolve bunch tails). Study variations of beam parameters within a pulse and pulse to pulse.
After having established the transfer line nominal settings with the use of a pencil beam, the aim of this next stage is to complete the beam characterization with full current and check repeatability of the measurements.

RF settings should be fine-tuned for higher current. Beam parameters stability should be studied by acquiring and comparing measurement values at several points along one single beam pulse (modifying the acquisition gating) and also for different pulses. Output beam position, transverse emittances, average energy and energy spread variations should be recorded.

Figure 21 shows the nominal beam distribution in the longitudinal plane at the slit, and in the transverse plane at the SEM grid (x-profile only). An initial energy spread of 57 keV (90% value) is coupled through the dispersion in the spectrometer line to a horizontal width at the SEM grid of ~10mm, with a measured energy resolution of about 6 keV/mm. For comparison, a beam distribution with artificially zero energy spread at the slit would yield a beam spot on the dump of approximately 2.7mm in size.

The two quadrupoles in the spectrometer line have been set in this case at -2.8 and 1.2 T/m. At the time of commissioning, the field values of these magnets should be chosen to improve the sensitivity of the Dp/p measurement, the ideal optics of the line being the one that maximizes the dispersion contribution (and minimizes the betatron one) to the final beam transverse size.

**Milestone**: test performance reliability with a full current beam.
STAGE 4:

Aim: characterize chopper functionality (time integrated)

Setup: MEBT+test bench, pencil beam, chopper ON DC, dump out

Planned schedule:

<table>
<thead>
<tr>
<th>Tasks</th>
<th>shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Voltage calibration on chopper plates (2\textsuperscript{nd} buncher and central quadrupoles off): measure beam centroid position on WS and transmission. Beam-based measurement of field coverage factor.</td>
<td>3</td>
</tr>
<tr>
<td>4.2 Measure individual optics contributions to beam deflection, switching on one by one central quadrupoles and 2\textsuperscript{nd} buncher): measure beam centroid position on WS and transmission</td>
<td>5</td>
</tr>
<tr>
<td>4.3 Repeat (4.1) for full current beam</td>
<td>3</td>
</tr>
</tbody>
</table>

Procedure: Aim of this stage of commissioning is to study the beam deflection dynamics of the chopper on a pencil beam [6]. Initially, a voltage calibration of the chopper plates should be carried out, with all optical elements switched off, by measuring the sweep in the beam centroid position at the second wire scanner and the variation in beam transmission at the test bench as a function of the voltage applied to the plates. The same study should then be repeated for the following optics settings:

- L4L.QDB3090, L4L.QDB3110, L4L.QFC3130, L4L.BUN3120 off
- L4L.QDB3110 on
- L4L.QDB3110, L4L.BUN3120 on
- L4L.QDB3090, L4L.QDB3110, L4L.QFC3130, L4L.BUN3120 on

...to measure the individual effect of the magnets and bunchers in the line on the beam deflection (optically enhanced).

Fig.22 illustrates the separation (in the y-y’ and x-y plane) between the fully transmitted beam and the beam deflected by the chopper when a 500V effective voltage is applied to its plates for the four optics configurations listed above.

Fig.23 shows results of simulation studies for the variation of the beam centroid offset as measured at the wire scanner near the chopper dump (left) and the beam transmission at the transformer near the end of the chopper line (right) when the effective voltage applied to the chopper plates is varied between 0 and 800V for the same optics configurations examined above. Unity in the voltage factor scale (horizontal axis) corresponds to 500V.

Comparison of experimental measurements to these curves should provide a cross-check of the correct tuning of the elements in the line and beam-based calibration of the voltage applied to the chopper plates. As last step, the voltage calibration (with all other elements switched off) should also be repeated for a full current beam to obtain a beam-based measurement of the field coverage factor on the plates.
Figure 22  Separation in the y-y’ and x-y plane between the nominal beam distributions of the fully transmitted beam (chopper off) and a deflected beam when a 500V voltage is applied to the chopper plates. Several optics cases are presented.

Figure 23  Beam centroid offset at the wire scanner near the chopper dump and transmission on the transformer at the end of the chopper line as a function of the effective voltage applied to the chopper plates for different MEBT optics configuration.

Milestone: establish time-integrated chopper functionality.

STAGE 5:

Aim: Time resolved chopper functionality.

Setup: MEBT+test bench, full current beam, chopper on AC, various chopper schemes.
**Procedure:** test time resolved chopper functionality by measuring residual H- population in chopped buckets with Masaki’s detector. Measure intensity of partially chopped beam, chopping efficiency, rise/fall times with beam.

**Planned schedule:**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Study residual H- population in chopped buckets with the halo monitor: measure intensity of partially chopped beam, chopper efficiency, rise/fall times within pulse.</td>
<td>5</td>
</tr>
<tr>
<td>5.2 Compare emittances and profiles for chopped and unchopped beam</td>
<td>3</td>
</tr>
</tbody>
</table>

Aim of this phase of commissioning is to test the time resolved functionality of the chopper, by measuring the relative population of chopped and un-chopped (or partially chopped) bunches (see Fig.24).

Measurements will be taken on the halo detector [7], which has a gating resolution of 1 ns and can thus resolve adjacent bunches in a 352MHz train. Its dynamic range in intensity, of the order of $10^6$, allows a monitoring of beam losses at the level of 1W/m (currently assumed activation limit for mega-Watt scale beam facilities [8]).

The detection of partially chopped bunches will provide beam-based calibration of the rise and fall times of the chopper pulses and also a measurement of the residual intensity of the so called ‘ghost’ bunches, that will eventually be lost in the machine, for machine activation studies [9].

Several different chopping schemes should also be studied for test of timing sequences, later needed for synchronization with the PSB and injection painting schemes.

Measurements of the transverse emittances and profiles of the beam transmitted to the test bench should be taken for beam quality comparison between the cases with the chopper ON and OFF.

![Figure 24 Train of fully transmitted and not completely chopped bunches (352MHz frequency).](image)

**Milestone:** verify time resolved chopper functionality and beam quality for chopper ON/OFF
STAGE 6:

**Aim:** Study matching to the DTL.

**Procedure:** Assess tolerance margins on the DTL input beam.

**Planned schedule:**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Compare the measured final beam parameters to the expected acceptance of DTL tank1 in the three planes.</td>
<td>1</td>
</tr>
</tbody>
</table>

Aim of this phase of the commissioning is to verify that the final beam parameters measured at the exit of the chopper line fall within the expected acceptance window of the DTL Tank1 in both longitudinal and transverse planes.

Tolerance margins have been evaluated with simulation studies. The longitudinal plane was probed with a pencil beam scanning technique, by studying the transmission of input beam distributions with a centroid offset in average energy and synchronous phase.

Fig. 25 shows in blue the nominal beam at the MEBT output; in red are the phase space locations of input beam centroid positions of beams that are transmitted by Tank1 with a final energy above 10.5MeV. The plot shows a maximum acceptance window of approximately ±0.2MeV in energy and -30/+40 deg in phase, comfortably bigger than the expected phase and energy deviations within the tuning range of the MEBT buncher cavities (see Fig.9 for comparison).

![Figure 25 Tank1 longitudinal acceptance.](image-url)
Figs 26 and 27 show in blue the DTL Tank1 acceptance in the X-X' and Y-Y' transverse planes. These distributions have been obtained by tracking a virtual uniform beam with very large horizontal and vertical beam sizes respectively, and point-like in the two other planes. The acceptance is then given by the phase space of the input beam coordinates (in the plane under study) of the surviving particles, according to a method described in [10]. Overlapped in yellow are the ellipse contours of the 90% emittance nominal beam distributions at the end of the chopper line, and in red the same ellipse contours in the case that one of the quadrupoles in the last MEBT F0D0 channel is varied within ±20% of its nominal gradient setting, while the other 3 are kept at their nominal values (with similar procedure to the one used to produce the plots in Fig.18). Final Twiss parameters α and β values are correspondingly varied by up to 50-100% or more. In the horizontal plane the sensitivity is higher to L4L.QDA3220 settings, while in the vertical plane the same is true for L4L.QDA3200. Measured output beam conditions should be compared to these plots to assess the tolerance margins at the matching point with DTL tank1.

**Milestone:** verify matching conditions to the DTL before Tank1 installation.
Figure 27 Tank1 acceptance in the Y-Y’ phase space.

REFERENCES
