LINAC4 BEAM COMMISSIONING STRATEGY

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Abstract

Linac4 is a 160 MeV H⁻ ion linear accelerator, presently under construction, which will replace the 50 MeV Linac2 as injector of the CERN proton complex [1]. Linac4 is 90 meters long normal-conducting Linac made of a 3 MeV Radio Frequency Quadrupole (RFQ) followed by a 50 MeV Drift Tube Linac (DTL), a 100 MeV Cell-Coupled Drift Tube Linac (CCDTL) and a Pi-Mode Structure (PIMS). Starting in 2013, five commissioning stages, interlaced with installation periods, are foreseen at the energies of 3, 12, 50, 100 and 160 MeV. In addition to the diagnostics permanently installed in the Linac, temporary measurement benches will be located at the end of each structure and will be used for beam commissioning. Comprehensive beam dynamics simulations were carried out through the Linac and the diagnostics benches to define a commissioning procedure, which is summarised in this paper. In particular, we will present a method for emittance reconstruction from profile measurements which keeps into account the effects of space charge and finite diagnostics resolution.

INTRODUCTION

The commissioning of Linac4 is foreseen in 5 stages at the energies of 3, 12, 50, 100 and 160 MeV corresponding to the commissioning of the different accelerating structures. The measurement of the transverse beam emittance at each energy milestone will be an essential step during the commissioning of the Linac. At low energy (below 12 MeV – DTL tank1), as the beam penetration depth and activation are low, a direct method based on a slit and grid system is preferred. When the beam reaches energies of few tens of MeV the technical realisation of the slit becomes more challenging and therefore indirect methods to measure the emittance are preferred especially for a temporary measurement line. The classical emittance reconstruction technique, based on measuring the beam profile at three different locations [2], is reliable only if the emittance is conserved and there aren't any self-forces acting on the beam in between the 3 monitors. This latter condition is not fulfilled in the energy range 10-100 MeV for a beam which carries about 70 mA of peak current. To compensate for this drawback we have extended the classical method by combining it with an iterative process of multiparticle tracking which starts from upstream the suite of monitors and propagate the beam "forwards" taking into account space charge effects. This very efficient technique, which we call "forward method", is detailed in this paper and applied to the LINAC4 beam.

THE "FORWARD METHOD"

The forward method is a technique which aims at reconstructing the transverse emittance of a beam of particles at a given location by using information on the beam size measured at three locations downstream. It is assumed that no active elements are located after the point where the emittance is measured. This method consists of two main steps.

First Step, the 3 Monitor Method

The 3 monitor method is now well established and is detailed for sake of completeness. The beam envelope evolution can be represented by the sigma matrix, written as follow, assuming the three planes are uncorrelated.

$$\sigma = \begin{pmatrix} x_m^2 & x_e\, x_m' \\ x_e' x_m & {x_m'}^2 \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

If we define a transport matrix R of a beam line going from Z=0 to Z=L as:

$$R = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}$$

The relation between the sigma matrix at Z=0 and Z=L, assuming a constant emittance, is:

$$\sigma(L) = R * \sigma(0) * R^T$$

By introducing a monitor in the beam line, we can measure the first row – first column term and we have therefore the following relation:

$$x_{monitor}^2 = R_{11}^2 \epsilon\beta - 2R_{11}R_{12}\epsilon\alpha + R_{12}^2 \epsilon\gamma$$

If we measure the beam sizes at three different locations, we obtain a system of three equations similar to the one above. The transport matrices from reconstruction point to monitors being known, the emittance ϵ, and the Twiss parameters α and β can be found by solving the system of 3 equations. This method is fairly accurate if the beam line geometry is well known, the emittance constant and the transport matrix does not depend on the beam input characteristics. In presence of space charge, the latter condition is not satisfied, and this dependence can lead to substantial error in the emittance estimation. This potential error on emittance reconstruction is illustrated by figure 1. It shows, in blue, the horizontal rms beam envelope along the temporary commissioning bench after the 50 MeV DTL in presence of space charge (65 mA peak current). The dashed lines represent the location of the 3 profile monitors. The beam sizes at the location of the monitor are used through the 3 monitor method, and the input beam parameters reconstructed. The red line represents the envelope of the reconstructed beam simulated without space charge, the green line the envelope with space charge. Two information in this graph: first, the difference between the blue and the

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red/green lines at z=0 tells us that using only the 3 monitor method in presence of space charge is not accurate; second, the difference between the blue and green lines at the monitors tells us that the space charge self-forces depend quite strongly on the beam volume, and therefore, an iterative process is necessary.

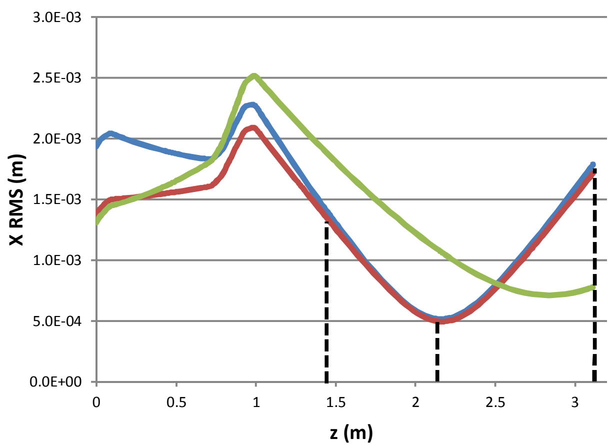

Figure 1: Nominal and reconstructed horizontal rms envelope at the Linac4 DTL output (50 MeV).

Second Step, Multiparticle Iterative Process

Before starting the iterative process, the three monitor method should have been applied in both transverse planes and starting conditions found at a common point. We can then generate a beam distribution for a multi-particle tracking code [3], knowing the Twiss parameters in both planes from the previous step and assuming a longitudinal distribution as we guess it at that point. Note that the choice of the distribution type (Gaussian, uniform, etc…) may influence the calculation by modifying the space charge forces distribution. A series of statistical runs is then launched by randomly varying the input alphas, betas and emittances parameters. At each run the beam sizes at the 3 monitors are compared with the measured values and a convergence criterion is given by the quadratic error:

$$\sqrt{\sum_i \left(\frac{x_{rms}^{meas} - x_{rms}^{tracked}}{x_{rms}^{meas}}\right)^2_{monitor\ i}}$$

The input Twiss parameters which minimize the function above, are retained. A detailed example of the method is given in the following section.

THE "FORWARD METHOD" APPLIED TO LINAC4

In view of the Linac4 commissioning preparation, a simulation campaign was performed at each beam energy stages in order to validate the forward method [4]. In particular the emittance reconstructed from the simulated profile measurements has been compared with the emittance as calculated directly from the particles coordinates. The example of the emittance reconstruction simulation at 50 MeV (DTL output) is detailed below.

Measurement Line Layout

For the 50 MeV commissioning stage, a temporary test bench will be installed after the third DTL tank. As shown in figure 2, it comprises 2 EMQs (electromagnetic quadrupoles), 2 corrector magnets (black rectangles) and 3 profile monitors (red rectangles).

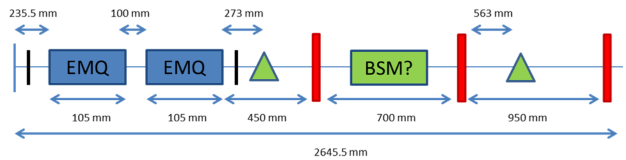

Figure 2: 30-50-100 MeV test bench layout.

The EMQs on the test bench and the one permanently installed after the DTL are used to generate a waist, in the plane being measured, at the location of the central monitor (see fig.1 for the horizontal plane). The 3 profile monitors (SEMGrids or WireScanners) are located at such distances that we can reach a 60° transverse phase advance from monitor to monitor. The following table summarizes the expected beam sizes at the monitors in such configuration. These beams sizes have been obtained by propagating the beam to the monitor and sampling it with the resolution of the monitor, including errors due to noise on detector wires signals [4].

Table 1: Expected Measured rms Beam Sizes at the Monitors

Beam sizes (rms)	**Hor. plane**	**Vert. plane**
Monitor 1	1.37 mm	1.23 mm
Monitor 2	0.51 mm	0.73 mm
Monitor 3	1.78 mm	1.40 mm

The beam line is supposed to be well known (distances from magnets and diagnostics, quadrupole gradient). In this particular case, the quadrupole settings used for the horizontal and vertical plane measurement are different, the beam emittance has to be reconstructed upstream the first magnet. Table 2 gives the comparison between the reference and the reconstructed emittance parameters at that location after the classical method (no space charge included).

We can notice a large discrepancy between the transverse ellipses parameters in both planes (up to 2 for alpha and more than 50% for beta), as shown already in fig 1. To improve the accuracy a beam distribution is generated with the parameters found, considered as a starting point for the iterative process with the multiparticle tracking code. The beam line is simulated few hundred times including the space charge effect. At every run, the transverse beam parameters are randomly changed, and the beam sizes simulated at the monitor location recorded. The retained candidate is the input

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beam that minimises the convergence criteria defined in the previous paragraph.

Table 2: Reference and Reconstructed Emittance Parameters after Step 1

Twiss parameters	Reference	Reconstructed
α_x	-5.51	-3.67
β_x	4.38 mm/mrad	2.22 mm/mrad
ϵ_x (Norm. rms)	0.28 mm.mrad	0.30 mm.mrad
α_y	2.77	1.03
β_y	1.69 mm/mrad	0.66 mm/mrad
ϵ_y (Norm. rms)	0.29 mm.mrad	0.32 mm.mrad

The reference and reconstructed transverse ellipses parameters are listed in table 3. After the second step of the forward method, we can notice a good convergence between the reference and reconstructed beam parameters (better than 0.2 for alpha, 5% for beta and 4% for the rms emittance).

Table 3: Reference and Reconstructed Emittance Parameters after Step 2

Twiss parameters	Reference	Reconstructed
α_x	-5.51	-5.61
β_x	4.38 mm/mrad	4.57 mm/mrad
ϵ_x (Norm. rms)	0.28 mm.mrad	0.29 mm.mrad
α_y	2.77	2.95
β_y	1.69 mm/mrad	1.78 mm/mrad
ϵ_y (Norm. rms)	0.29 mm.mrad	0.29 mm.mrad

The beam distributions in the transverse phase spaces are shown in figure 3. The reference beam is shown on the left, the reconstructed after the first step in the middle and after the forward method on the right. Note that the halo is not present in the reconstructed beams which are generated with Gaussian distributions.

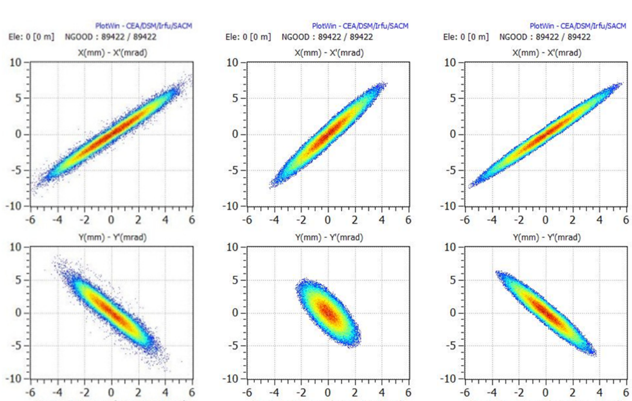

Figure 3: Beam distribution in transverse phase spaces.

Once again, we can notice the improvement in the emittance parameters estimation brought by calculating the space charge effects in forward mode.

DISCUSSION

The forward method was simulated and validated at each beam commissioning energies. In each case, the transverse emittances parameters calculated directly from the simulated beam particles coordinates and the one reconstructed from profile measurements differ by less than 5%.

The need for the forward method really depends on the intensity of the space charge effect, meaning mainly on peak current, bunch volume and energy. In the case of Linac4 commissioning, 70 mA, small beam size and energies from 3 to 160 MeV, this method is essential to be able to set the transverse parameters of the machine. In a low space charge regime, for example at 160 MeV and when the beam is debunched at the PS Booster injection, the classical three monitor method can be applied stand alone. In any case, a crosscheck of the results with multiparticle beam dynamics tools is always needed to validate the measurements.

CONCLUSION

We have developed a method for the transverse emittance measurement in a space charge dominated regime which we will apply during the Linac4 beam commissioning. The results obtained are very encouraging and they highlight the importance of including the space charge effect in our calculation. A key point of the forward method is the generation of the multiparticle beam distributions in the three dimensions that define the beam volume and consequently the space charge forces. A good knowledge of the longitudinal plane distribution is necessary for predicting accurately transverse beam parameters. If necessary, the longitudinal parameters can be statistically varied to better match the measurements at the expenses of longer computer time.

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