ACCURACY DETERMINATION OF THE CERN LINAC4 EMITTANCE MEASUREMENTS AT THE TEST BENCH FOR 3 AND 12 MEV

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Abstract

The CERN LINAC4 commissioning will start in 2011, at first in a laboratory test stand where the 45 KeV H^- source is already installed and presently tested, and later in the LINAC4 tunnel. A movable diagnostics bench will be equipped with the necessary sensors capable of characterizing the H^- beam in different stages, from 3 MeV up to the first DTL tank at 12 MeV. In this paper we will discuss the accuracy of the transverse emittance measurement that will be performed with the slit-grid method. The system's mechanical and geometric parameters have been determined in order to achieve the required resolution and sensitivity. Space charge effects during the beam transfer from the slit to the grid and scattering effects at the slit have been considered to determine the overall emittance measurement accuracy.

INTRODUCTION

For low energy linear accelerators, a typical method for measuring the transverse emittance consists in a slit and grid system. As shown in Fig. 1, for each slit position, the narrow aperture allows the passage of a beamlet populated by particles that have an almost equal position x and a certain angular distribution. In the following drift space, the beamlet angular distribution is transformed into a position distribution and sampled using a profile monitor, in our case a wire grid. The profile measurement determines the angle x' (y') for a certain position x (y) and by scanning the slit across the beam the whole phase-space can be reconstructed.

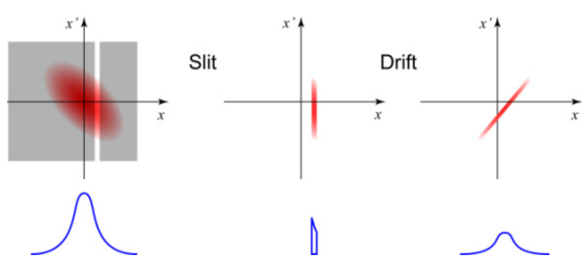

Figure 1: Phase space sampling with a slit and grid system.

The profile monitor resolution and the drift length, which modifies the phase space rotation, determine the angular resolution of the system. The slit geometry and material affects the measurement accuracy. A number of particles will be scattered on the slit aperture edges and the slit aperture width biases the phase space sampling by introducing an angular cut.

At low energies, the space charge effect has a strong influence on the beam dynamics and an emittance increase is expected along each drift space. Since such an effect is proportional to the beam current, the smaller the slit aperture, the smaller the emittance measurement perturbation.

All these aspects will be discussed in the next sections considering the design of the LINAC 4 test bench emittance meter that will be equipped with:

- two slits (1 per plane) made of graphite blades, with the possibility of setting the slit aperture to 100 or 200 μm during the assembly [1];
- two grids with 48 Carbon wires each, mounted 0.75 mm apart, installed 3.5 m from the slits.

Stepping motors will drive slits and grids.

SLIT APERTURE

In transverse phase space, given the Courant-Snyder invariant:

$$\epsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2 \tag{1}$$

where α, β and γ are the Twiss parameters at a fixed location and ε the geometric RMS emittance, one can calculate the emittance error due to the finite slit aperture Δx = e according to:

$$\frac{\Delta x'}{\Delta x} = \frac{-\alpha}{\beta} \quad \text{and} \quad \frac{\Delta\varepsilon}{\varepsilon} = \Delta x' \frac{1}{\sqrt{\varepsilon/\beta}} = \frac{-\alpha e}{\beta}\frac{1}{\sqrt{\varepsilon/\beta}} \approx \frac{\alpha e}{\sqrt{\beta\varepsilon}} \approx \frac{\alpha e}{\sigma} \tag{2}$$

With the nominal emittance and Twiss parameters at the slit, for the three measurement stages foreseen for the diagnostics bench, the emittance errors for a slit with aperture e=200 μm are listed in Table 1. For each location the horizontal plane is the most critical. At the MEBT and DTL locations, the predicted error is above 6 %. With a slit aperture e=100 μm, the error would be below 3.7 %, but such a small gap would worsen the signal over noise level at the wire grids.

Table 1: Relative Emittance Measurement Error Due to the Finite Slit Aperture e=200 μm

	RFQ		MEBT		DTL	
	H	V	H	V	H	V
Δε / ε [%]	1.2	0.1	7.41	0.7	6.4	2.8

SLIT THICKNESS

The slit thickness along the beam trajectory coordinate affects the measurement accuracy, due to the angular cut that is introduced. Figure 4 shows the maximum particle transmitted angle ϑ_{cut} after the slit as function of the slit thickness d (for a slit aperture of e=0.1mm), calculated as $\vartheta_{cut} = e / (2\cdot d)$.

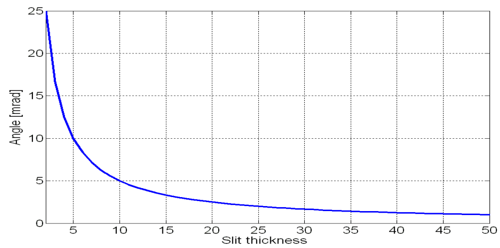

Figure 2: Maximum transmitted angular distribution due to the slit thickness.

At the diagnostics bench slit, a maximum beamlet divergence of 8 mrad is expected. A slit thickness smaller than 5 mm accepts angles up to 10 mrad and does not affect the measurement. The minimum thickness depends on the slit material. Since in graphite 12 MeV H^- ions are stripped after few nanometers and the protons are absorbed after 1 mm, the minimum slit thickness can be set to 2 mm.

SPACE CHARGE

A beam size increase due to space charge effects, along the drift from the slit to the grid, can perturb the emittance reconstruction. The effect increases for decreasing energies and since it increases for higher particle density, the measurement error increases for large slit apertures and small beam sizes. The tracking code PATH has been used to simulate such an effect for the MEBT and DTL cases in the horizontal plane. The case at 3 MeV has also been simulated considering a hypothetical higher density beam (MEBT II). The relevant beam parameters of the distributions simulated are summarized in Table 2.

Table 2: Beam Parameters at the Slit, for the Three Cases Studied with Space Charge

	MEBT	MEBT II	DTL
Current [mA]		65	
Energy [MeV]	3	3	12
Norm. Emitt. [mm mrad]	0.3	0.28	0.3
RMS size [mm]	3.3	2	1.2

PATH has been setup with a perfect slit (no scattering, no angular cuts), the 3.5 m drift space and a scoring plane at the grid location. The slit scans have been simulated by displacing the beam at the slit location. With 21 steps, it was guaranteed to have at least 4 slit positions per beam RMS width. For each slit position, the beamlet has been scored at the grid with and without space charge effects. Regardless of the number of tracked particles, PATH simulates space charge according to the total beam intensity. The beamlet distributions scored at the grid have been fed to a routine designed to reconstruct the RMS emittance, assuming an infinite resolution monitor. This has been repeated for the two slit apertures e=100 μm and e=200 μm. The results are shown in Fig. 3.

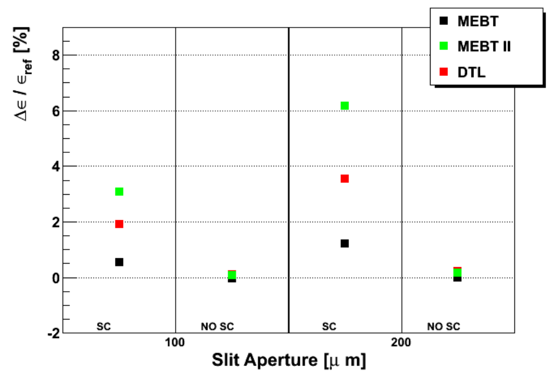

Figure 3: Emittance reconstruction error due to space charge, considering two slit apertures.

The simulation statistical error when assuming a infinite resolution monitor is below 1 %, as can be inferred by the results without space charge. The emittance overestimation due to space charge is less than 0.6% in the MEBT case for a slit aperture e=0.1 mm and doubles for e=0.2mm. At the same energy with a smaller beam (case MEBT II), the error is almost 6 % for the larger slit aperture. For the DTL, even though the beam energy is higher (space charge diminishes with energy), the higher particle density yields to a space charge emittance increase of the order of 2 % and 4 % for the two slit apertures respectively.

PROFILE MONITOR RESOLUTION

In order to simulate the effect of profile monitor resolution, the distributions scored at the grid location have been grouped according to the following cases:

- 50 um wide bins, one contiguous to the other, covering the all profile;
- 50 um wide bins separated by 250 um;
- 50 um wide bins separated by 750 um.

This corresponds to have different wire distances. At each slit step, the slit position x and the beamlet divergence x' calculated from the RMS of the bin amplitudes have been used in the emittance reconstruction routine.

The results are shown in Fig. 4, for a slit aperture of 200 μm. With no space charge included in the simulation, a wire distance of 750 μm induces a 3.5 % error on the emittance for the case where the beamlets have smaller divergence (MEB II). For 250 μm wire distance, the maximum estimated error is 0.5 % and it is dominated by the statistical error due to the limited number of particles per bin. The statistical error is particularly significant when the slit samples the beam halo. For 50 um wire distance, the errors are below 0.2% despite the low statistics.

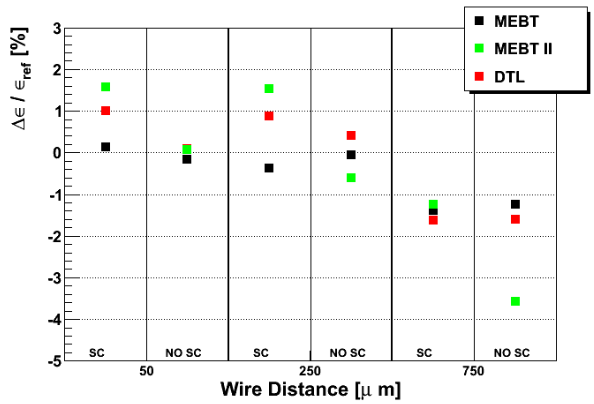

Figure 4: Emittance reconstruction error due to the profile monitor resolution, with and without space charge.

With space charge included in the simulations, the total estimated error is a superimposition of the induced blowup, the wire sampling effect and the statistical error. The maximum error is of the order of 1.5 % for the MEBT II case with 50 μm (reproducing the infinite resolution monitor case with space charge effect of Fig. 3) and 250 μm wire spacing. Always considering the MEB II case, the error due to the worse sampling (750 um wire spacing) is partially compensated by the emittance increase due to space charge.

SCATTERING

The Monte Carlo simulation package FLUKA [2] has been used to study the effect of particles scattering along the slit aperture. The same particle distributions as the ones used for the tracking studies above have been fed to the FLUKA model, consisting of a graphite slit with an aperture of 100 or 200 μm and a thickness of 3 mm. The FLUKA output has then been used for tracking to the profile monitor and the emittance reconstruction.

Due to the low H^- energy, all scattered particles reaching the profile monitor can be considered as fully stripped. At 3 and 12 MeV the H^- signal on the wires is dominated by the charge deposition of the two electrons [3], to which scattered particles will not contribute. At 3 MeV the average kinetic energy of the scattered ions is about 2 MeV and they are stopped in the Carbon wire. In this case the wire signal is given by both secondary emission at the surface and direct charge deposition of the proton. The charge creation is +1.75 electrons per proton hitting the wire, while a H^- ion deposits -1.2 charges.

At 12 MeV, the average energy of the scattered ions is around 8.5 MeV and the protons have good probability of exiting the wire. In this case, the wire signal is only given by secondary emission. The signals are +0.292 per proton and -1.8 for an H^- ion.

These considerations have been used to give a weight to each particle reaching the profile monitor, in order to properly simulate the expected wire signal. The emittance reconstruction results, as simulated for the MEBT and DTL cases, for two slit apertures and for different profile monitor resolutions, are shown in Fig. 5.

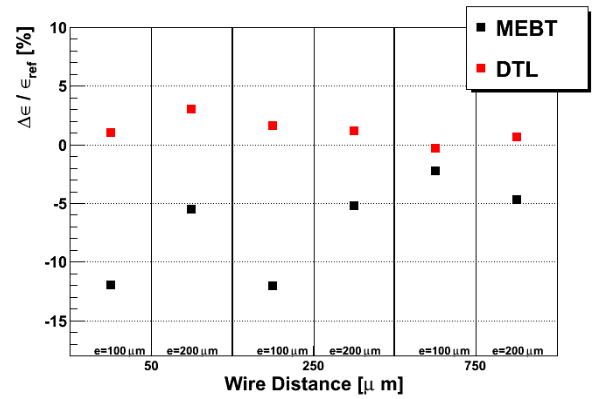

Figure 5: Emittance reconstruction error due to scattering at the slit, for two slit apertures, three wire distances and no space charge effects.

The background due to scattered particles spreads uniformly over the profile monitor acceptance and its level is almost the same for the 2 H^- energies and for the 2 slit apertures.

At 12 MeV, the effect of the scattered particles on the emittance reconstruction is negligible, and cannot be separated from the statistical error due to the finite number of particles in the simulation.

For the 3 MeV case, the higher weight of the scattered protons on the wire signal induces an error on the emittance reconstruction, that is 12% and 5% for a slit aperture of 100 μm and 200 μm respectively. This is true for a wire distance of 50 and 250 μm, while for 750 μm the error is partially compensated by the reconstructed emittance increase due to the poor monitor resolution.

CONCLUSIONS

The finite sampling resolution due to the slit aperture can induce a 6 % error on the emittance reconstruction. A minimum graphite slit thickness of 2 mm guarantees no angular cuts for all expected beamlet divergences. The maximum error due to space charge is about 4 % for the DTL case, with nominal beam parameters, but would increase in case higher density beams will be delivered. The error due to the limited intrinsic profile monitor resolution, given by the 750 μm wire spacing, can be avoided by scanning several grid positions for each slit step. The error due to background from particles scattered at the slit can reach 12 %, but can be minimized by developing a background subtraction algorithm.

REFERENCES

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[2] A. Ferari et al., "FLUKA: a multi-particle transport code", CERN-2005-10 (2005).

[3] F. Roncarolo et al., "Wire grid and wire scanner design for CERN LINAC4", These proceedings.