HIGH POWER AND HIGH DUTY CYCLE SLIT AND GRID SYSTEM FOR HADRON ACCELERATOR COMMISSIONING

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INTRODUCTION

Transverse emittance is one of the key measurements to be performed during the commissioning of the low energy sections of an hadron linac. The good knowledge of the beam transverse phase space allows a safe and efficient operation of the machines by using the results of the measurement for beam dynamic simulations.

In this paper we will discuss the accuracy and the limits of the transverse emittance measurement performed with the slit-grid method based on the ESS beam parameters at the RFQ (beam energy equal to 3.62 MeV) and DTL tank 1 (beam energy equal to 21 MeV) output [1]. The goal of this paper is to set the limits of the operating domain of the slit and grid system in machine similar to ESS, in particular to achieve emittance measurement with a beam pulse length up to 1 ms. The authors assume that the emittance will be measured on a diagnostic test bench with a matching sections.

In the following the emittance is referred to the RMS normalized emittance, the slit geometrical parameters are summarized in Fig. 1 for reference, the angle of the slit is the angle between one slit blade and the z-axis of the beam.

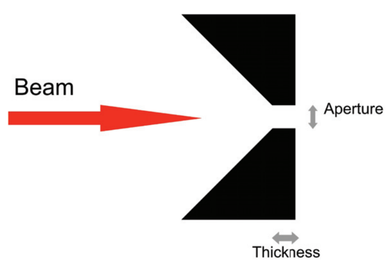

Figure 1: Schematic diagram of the slit used in the simulations (dimensions are not on scale).

BEAM DISTRIBUTIONS

At the exit of the RFQ and the DTL, beam sizes are too small to use interceptive devices with pulses longer than 20-50 μs. In order to reach relatively high duty cycle, the beam sizes at the slit location must be increased to reduce the thermal load, in addition the beam divergence has to be kept small enough to avoid angular cut in the transverse phase space during the emittance measurement, in a ideal case, the beam shall be parallel in both transverse planes, thus to expand the beam with small emittance increase and keep the divergence small enough a triplet of quadrupoles is mandatory.

Based on these specifications and similar quadrupoles characteristics from other facilities, preliminary simulations were performed with the TraceWin code [2] in order to generate beam sources which can be used as input for all the studies presented in this paper. Without a full optimization of the beam dynamics, these inputs have been considered as test cases for the design of an emittance meter. The Fig. 2 and Fig. 3 show the transverse phase spaces for the RFQ and DTL at the output to the triplet, the Twiss parameters are summarized in Table 1.

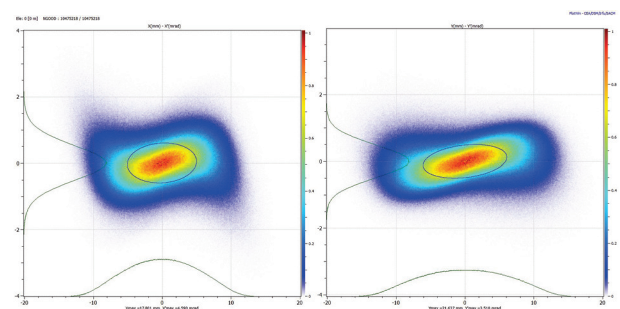

Figure 2: Transverse phase space distributions at the end RFQ matching section.

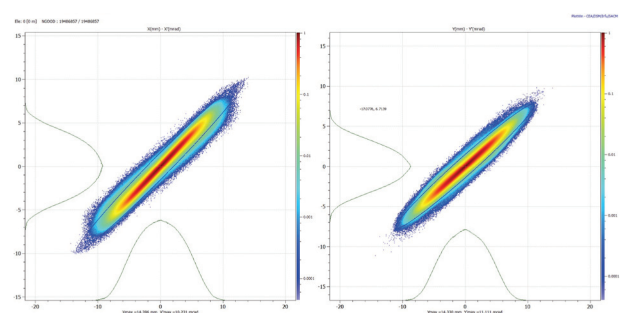

Figure 3: Transverse phase space distributions at the end DTL matching section.

Table 1: Beam Parameter Expected at 150 mm Upstream The Theoretical Slit Position For The RFQ and DTL Cases

Location	RFQ		DTL	
Plane	H	V	H	V
α	-0.076	-0.216	-6.19	-5.25
β [mm/πrad]	8.41	12.52	8.58	7.64
$\varepsilon_{norm.}$	0.2633	0.2601	0.3303	0.3103

In both cases, the beams have been transported form the RFQ entrance to the end of the matching section, The particles distributions are taken at 150 mm upstream the theoretical slit position in order to reserve space for mechanical integration.

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PRELIMINARY ESTIMATION OF THE THERMAL LOAD

Thermal load on the slit is one of the most critical point of the design of an emittance meter. Based on experience learn from LINAC4 slit and grid system, graphite or more generally low density materials are the best options for the slit material, the slit can be tilted to decrease the beam power density and thus reduce the thermal load [3].

For this study, slit and grid system will be mainly derived from the LINAC4 design, an optimization of the slit is nevertheless mandatory to cop with the higher beam power of the ESS linac. In this preliminary estimation of the temperature, only R4550 graphite has been simulated, the angle of the slit w.r.t the beam axis is set to 15 degrees. A 3D energy deposition map has been generated with the Monte Carlo (MC) code FLUKA [4] and then use as an input a Finite Element (FE) analysis with the ANSYS applications. Based on the LINAC4 experience, the temperature shall not exceed 1300 K to insure mechanical integrity of the slit.

3.62 MeV Beam

For a 1 ms pulse length, the peak temperature is$\approx$ 1000 K, in this case it might be possible to increase even more the duty cycle without approaching the mechanical limits of the R4550 graphite. It is interesting to note that the results from FE analysis presents a big discrepancy compare the temperature estimation with an analytical model without conduction, and that the temperature gradient in the slit decreases with time even during the pulse.

In order to check the influence of thermal conduction on the results, a new set of FE simulations have been performed. In a first step, the thermal conduction of the slit material was reduced by 6 order of magnitude in FE models, as consequence, the results of this simulations and the the results of the analytical model show a difference at a percent level, which can be explain by some difference in the specific heat capacity model. Unlike the previous FE model, the temperature gradient is clearly visible at all time step on the temperature map, showing that the coupling between ANSYS and FLUKA is correctly done, conductive cooling for this beam energy seems efficient even at small time scale. A similar behavior has been reported for the LINAC4 slit design in [5] , other authors reports a high efficiency of the thermal conductivity for low energy protons beam.

21.3 MeV Beam

The thermal conductivity is less efficient in this case, the difference between the analytical model and FE model is less than 20 %. With a higher beam density compare to the RFQ case ($\approx$ 3.5 mm) the slit can not withstand a pulse length of 1 ms, the temperature is slightly above the limit after 500 μs (T_{max} = 1570 K). Increasing the beam sizes to 6 mm allows the slit to withstand a higher duty cycle, the peak temperature is around 1150 K at the end of a 1 ms beam pulse, nevertheless, the α parameters of such beam are over the acceptance of the slit and grid system, as consequence this case is not considered in this paper, more detail can be found in [6].

ERROR ON THE EMITTANCE RECONSTRUCTION WITH A SLIT AND GRID SYSTEM

The slit and grid method for measuring the beam transverse phase space might induced some errors in the emittance reconstruction, in this paper, we propose to discuss the influence of the error on the slit/grid position and the influence of Multiple scattering on the slit edges.

Error on Slit and Grid Positioning

The positions of the slits and the grids have to be measured with a good accuracy to reduce the error on the emittance reconstruction.

Vertical and horizontal emittance scans have been simulated for different distance between the slit and the grid (from 600 mm to 4000 mm in step of 100 mm), the transverse beam position is sampled in step of 0.5 mm. The monitor consists in a grid equipped with 100 μm diameter wires and a pitch equal to 500 μm. The signal is assumed to be equal to be the number of particles crossing each wire. The slit aperture was set from 100 μm to 500 μm in step of 100 μm.

Random error has been applied to each couple: slit position-wire position (i.e. angle). The errors are assumed to be gaussian with an RMS value from 0 to 100 μm. in step of 10 μm for the grid and in step of 50 μm for the slit. For each slit-grid distance, 50 virtual emittance scans have been performed, the average ϵ_{RMS} over these 50 scans has been be compared to the reference emittance given in Table 1.

RFQ A first estimation of the emittance has been done without error on the slit/grid position for the different slit aperture and wire diameter in both transverse planes. As shown in Fig. 4 the error is independent of the slit aperture, small variation can be explain by statistical error. It can be observed that the error seems to be more or less constant for distance between the slit and the grid longer than 1000 mm, the error in this case is less than ± 0.2 %. Similar results can be observed in the vertical plane.

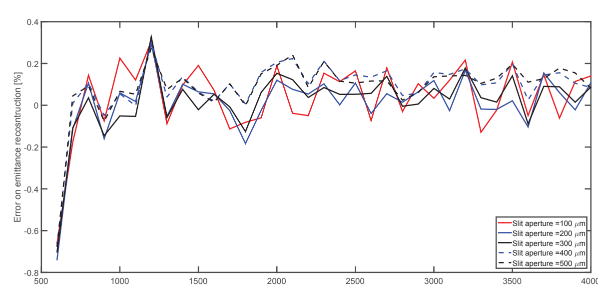

Figure 4: Error on horizontal emittance reconstruction as function of the slit and grid distance for different slit aperture. the wire diameter is 100 μm

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With an α close to 0, the influence of the slit aperture on the emittance reconstruction can be neglected, to improve the statistics of the simulations, all the results presented in the following have been estimated with a slit aperture of 500 μm and a wire diameter equal to 100 μm.

As shown in Fig. 5, with error on the grid and slit position the distance between the slit and the grid has to be increase to reduce the error on the reconstructed emittance below an acceptable level.

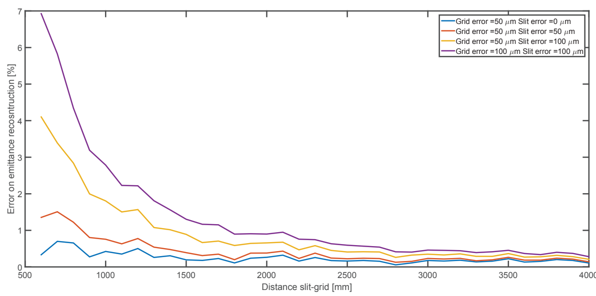

Figure 5: Error on horizontal emittance reconstruction as function of the slit and grid distance for different couple of errors on grid position and slit position, the slit aperture is 500 μm and the wire diameter is 100 μm.

With an error on grid and slit position equal to 100 μm, the error on emittance reconstruction is less than 1 % if the distance between these tow elements is above 2.5 meters. Increasing the slit and grid position accuracy to 50 μm will improve the accuracy of the whole system.

A distance of 3000 mm between the slit and the grid has been taken as reference fro the Monte Carlo simulations presented in the next sections. It has to be noted that during the commissioning the beam might not be Gaussian, with 3 meters between the slit and the grid, the beamlet can be sample with 3-4 wires per sigmas (in a single shot measurement), which allow a sufficient angular resolution.

DTL As shown in Fig. 6, in the DTL case the silt aperture has a higher influence on the emittance reconstruction, if the distance between the slit and the grid is above 2500 mm, the error is less than 4 % and down to $\approx$ 1 % for the thinner slit aperture. As for the RFQ case, the wire diameter is not influencing the emittance reconstruction, the same distance between the slit and the grid has been also chosen for the next simulations (3000 mm).

Multiple Scattering Effect

Multiple scattering on the slit edges can affect the measurement accuracy and lead to over estimated the beam transverse emittance, the Monte Carlo simulation package FLUKA has been used to study this effect.

The sources generated by the TraceWin code have been used as input for the simulations, in order to simplify the post processing, the beam is considered as mono energetic. The aperture and the thickness of the slit are free parameters the angle of the slit is set at 15 degrees, the SEM grid is

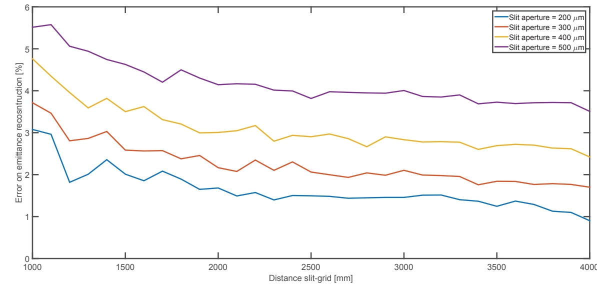

Figure 6: Error on horizontal emittance reconstruction as function of the slit and grid distance for different slit aperture, the wire diameter is 100 μm. Error on grid position and slit position is set to 50 μm, the sampled distribution is shown in Fig. 3.

simulated as a screen positioned 3 meters downstream the slit, the position and the energy of each particle crossing the screen are measured, all particles with an energy smaller than the input energy are considered scattered. The results of the Monte Carlo code have been then used to estimate, in post processing, the beamlet profile sampled on a SEM grid with a pitch of 500 μm and a wire diameter of 100 μm. In a first step, a single slit position has been simulated, to reduce statistical errors, the slit is centered at 0, then full emittance scans have been simulated.

The influence of Multiple scattering on emittance reconstruction increases with the beam energy, thus the slit has to be design to reduce the error for a 21 MeV beam.

DTL The slit aperture varied from 100 μm to 500 μm and the slit thickness from 1 to 3.5 mm. As shown in Fig. 7 for a slit aperture equal to 100 μm, the proportion of scattered particles is strongly dependent of the slit thickness [1]. With a 2 mm thick slit the ratio is at the percent level, there is almost no difference between 3 and 3.5 mm, with a ratio close to 10^{-3}.

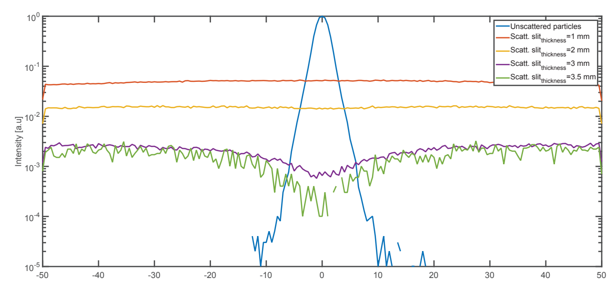

Figure 7: Scattered and un scattered particle distributions at the SEM grid location, for the slit in position x=0 for different slit thicknesses and a slit aperture equal to 100 μm (beam energy is 21.3 MeV).

The influence of the slit aperture has been also simulated with a slit thickness equal to 3 mm, the results are presented

[1] if this parameter is below 1 mm, the ratio of scattered particles can be up to 25 %

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in Fig. 8. Up to an aperture equal to 400 μm, the ratio of scattered particles decrease almost linearly as the slit aperture increases. The difference between 400 μm and 500 μm is relatively small, mainly due to lack of statistic. For a given slit thickness, the number of scattered particles is almost independent of the slit aperture, thus the ratio scattered/unscattered decreases as function of the slit aperture.

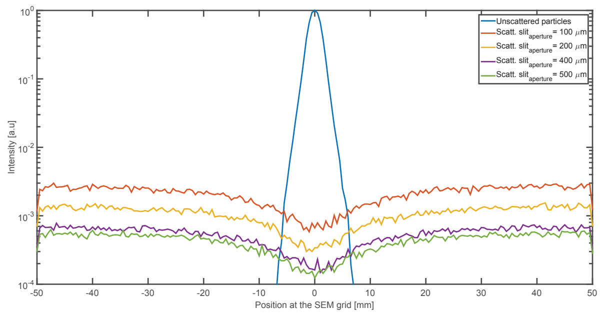

Figure 8: Scattered and un scattered particle distributions at the SEM grid location, for the slit in position x=0 for different slit apertures, the slit thickness is equal to 3 mm and the beam energy to 21.3 MeV.

The source of scattered particles has two origins, a first one is dominant when the slit thickness is below the penetration range of proton in the slit material, some particles have enough energy to cross the slit material and reach the SEM grid. The second origin is particles scattered on the slit edges, with a perfect slit (i.e no thickness) and neglecting the first source mentioned, all particles selected by the aperture shall not be scattered, in reality, a small fraction of these particles interact with the slit due to their divergences. The effect is relatively small but increases with the slit thickness and becomes dominant for slit thickness larger that the particle penetration depth in the slit material.

Reducing the slit aperture will improve the accuracy of emittance reconstruction and but to avoid angular cut the slit thickness shall be also reduced at the same time, it will be beneficial to use a higher density material for the slit.

Unfortunately, few materials have similar thermal properties as the R4550 graphite. One option is to use a composite of carbon fiber and molybdenum (MoGr), recently developed for the LHC collimator upgrade, this novel material shows thermal properties close to graphite with a higher thermal conductivity, moreover with a density almost 2 times higher than the graphite (2.8 $g.cm^{-3}$ compare to 1.7 $g.cm^{-3}$), the slit thickness can be reduced [7].

3.63 MeV Beam For the lower energy beam and a 3 mm slit thickness in graphite, the ratio is almost one order of magnitude lower (10^{-4}) compare to the DTL case, the design is not driven by this case (see and Fig. 9).

Emittance Reconstruction In the MC simulations the SEM grid is fixed and the slit moved by 0.5 mm steps to cover all the horizontal plane, different slit parameters have been simulated, as well as different scattered particles weight (in

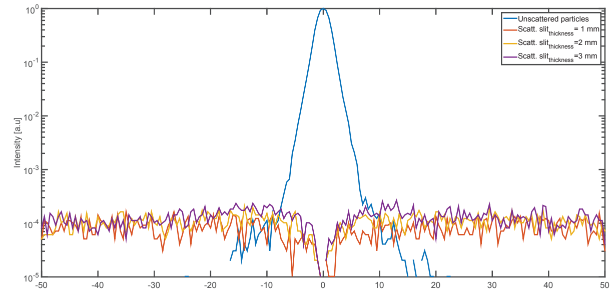

Figure 9: Scattered and un scattered particle distributions at the SEM grid location, for the slit in position x=0 for different slit thicknesses, the slit aperture is equal to 400 μm (beam energy is 3.63 MeV).

post processing). The normalized rms emittances have been estimated statistically, the results are shown in Table 2 and Table 3 for different slit parameters. Only the simulations performed in for the horizontal plane are presented, similar results are observed in the vertical plane.

Table 2: Error on Reconstructed Emittance With and Without Scattering Activated for the RFQ Case

Simulations parameters			Error on emittance [%]	
Slit ap.	slit th.	Grid pitch	Scattering	
[μm]	[mm]	[μm]	off	on
400	0	500	0.6	220
400	1	500	0.2	12.3
400	3	500	0.19	18

Table 3: Error on Reconstructed Emittance With and Without Scattering Activated for the DTL Case

Simulations parameters			Error on emittance [%]	
Slit ap.	slit th.	Grid pitch	Scattering	
[μm]	[mm]	[μm]	off	on
200	2	500	1.4	1295
400	2	500	2.7	990
400	3	500	2.8	862
400	3.5	500	2.7	385
200	3	500	-4.2	576

As show in Table 2 and Table 3, the statistical calculation of the rms emittance induce an important error if data is not treated, in particular for the DTL cases, particles far from the ellipse axis have a large impact on the rms emittance, alternative methods are needed to analysis the data. It has to be noted that the area of the transverse phase space sampled in the MC is much larger than what is need for a proper measurement ,as example, the sampling area of the beamlet is $\pm 15\sigma$ times the rms profile of the beamlet As consequence, since the scattered particles are spread in all

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the phase space samples in the MC simulations, the value on the reconstructed emittance is dominated by this effect .

It is interesting to note, that in the case of the thicker slit (3mm) with the smallest aperture, the emittance without scattering activated is underestimated, particles with high divergence angles are not properly measured, the rms beamlet profile is well reconstructed, but the beamlet "intensity" is reduced, leading to underestimate the contribution of these fraction of phase space on the rms emittance. Using a material with higher density like MoGr, will allow the reduction of the slit thickness to 2 mm, and used a thinner slit aperture. In this case, the error due to the reconstruction shall be less than 2 % with a limited contribution from multiple scattering.

DATA ANALYSIS

Several methods are available to analyze the data from an emittance scan, this section is describing few simple methods to remove the contribution of scattered particles and their application on the Monte Carlo simulations results, more complex algorithms can be applied to the data.

Data Thresholding

The most common and most simple method for emittance analysis is to apply a cut on the data. All the values below a given threshold will be excluded from the calculation, in general this threshold is a fraction of the peak signal obtain after the scan. For all the case presented in Table 2 and Table 3 the threshold need to match the reconstructed emittance without scattering activated is less than 0.5 % of the peak value.

Background Subtraction

A shown in Fig. 7 and Fig. 9, the distribution of scattered particles on the SEM grid is more or less flat. Since only few wires in the center of the SEM gird are needed to reconstruct the wire, the outer wire can be used to estimate the amount of signal generated by the scattered particles at the SEM grid location, them this signal can be subtracted to the data. Using this method will allow also to reduced the effect of the electronic noise on emittance reconstruction.

Phase Space Cut

The last method considered in this paper is refereed as "phase space cut", the goal of the method is to remove the data far form the emittance ellipse axis. A Gaussian fit is apply to each beamlet profile, then the data above 6 times above the sigma of distribution found with the fitting are excluded from the estimation of the emittance.

This 3 methods can be combined to improve the data analysis, some example are shown in Fig. 10 and Fig. 11.

For both energy cases, using a background subtraction together with a phase space cut allow to find the same value for the emittance as the one the one found with Monte Carlo Data when scattering is off without any threshold, error

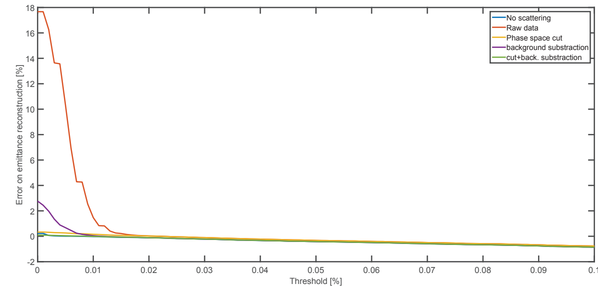

Figure 10: Emittance reconstruction as function of data threshold for different method of analysis. The beam energy is 3.63 MeV.

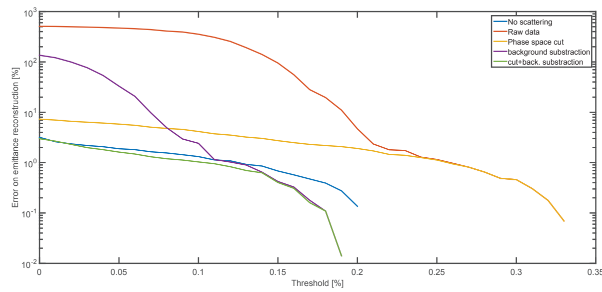

Figure 11: Emittance reconstruction as function of data threshold for different method of analysis. The beam energy is 21MeV.

compare to the "real" emittance (i.e. the one defined by the Tracewin distributions) is less than 2 %.

For the lower energy case, a threshold equal to ≈ 0.02 % on the data is needed to match the reference emittance for all the methods considered, at higher energy, a threshold equal to ≈ 0.1 % is needed to reach the matching point, but only for the background subtraction method and a combination of background subtraction and phase space cut. The other methods need a higher threshold and match the reference data only when the analysis gives a smaller emittance than the Tracewin values. With the proper method an error equal to ≈ 3 % is expected.

CONCLUSION

In high power hadron machine, the thermal load on interceptive instrument is one of the limiting factor for an increase of duty cycle during commissioning. After the preliminary studies presented in this paper, with an optimized slit design and an optimized beam dynamic, we can conclude that the emittance can be measured with pulse length longer than 400 μs and up to 1 ms at the exit of the RFQ with an error less than 5 % on the emittance reconstruction in machine with similar beam as ESS. Nevertheless to complete and confirm this preliminary study, it will be interesting to simulate the influence of the space charge on the emittance reconstruction. As final conclusion, the authors would like to emphasis that the best performance is achieved when the α parameter close to zero, in this case, the slit geometry has a small influence on the emittance reconstruction.

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