COMPARISON OF EMITTANCE GROWTH FOR 450 GeV RIGIDITY PB^{82+} IONS AND P+ IN THIN SCATTERERS

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Abstract

The beam profile screens in the long SPS-to-LHC transfer lines were used to measure with high precision the emittance growth arising from scattering. The effective thickness of the scatterer could be varied by adding thick Al_2O_3 fluorescent screens, with the emittance measurement made using very thin Ti OTR screens. The technique allows the intrinsic variation in the emittance from the injector chain to be factored out of the measurement, and was applied to Pb^{82+} and protons, both with 450 GeV rigidity. The results are presented and the possible applications to the accurate benchmarking of nuclear interaction codes discussed.

INTRODUCTION

The SPS-to-LHC transfer lines [1] used for both protons and lead ions are equipped with numerous beam profile monitors (BTVs), which have thick (1 mm) Al_2O_3 luminescence screens, and also thin (12 μm) Ti Optical Transition Radiation (OTR) screens. Eleven of these screens were used in TI 2 to make an accurate measurement of the emittance growth introduced by the thick Al_2O_3 screens, by using sets of four OTR screens to measure the emittance upstream and downstream of the Al_2O_3 screens in a single shot, with 0, 1, 2 or 3 Al_2O_3 screens placed in the beam to add different amounts of scattering material. The experimental method eliminates any shot-to-shot variation in emittance which might otherwise overwhelm the small signal, was insensitive to optics variations and also allowed the effects of different numbers of scattering screens to be investigated quantitatively. The opportunity was taken to compare the results obtained with protons and with fully stripped Pb^{82+} ions, with the same 1503 Tm rigidity.

In the following the experimental method is briefly outlined, together with a reminder of the technique for measuring emittance using a number of measured beam profiles, and the specifics of the measurement in the SPS-to-LHC lines. The details of the data taken and the results obtained are then presented. The simple scattering theory used to estimate the expected emittance growth is given, and the results of the measurements are compared with the expectations from this theory. Some conclusions are drawn, with a brief discussion concerning the results and a possible extension of the method.

EMITTANCE INCREASE FROM THIN SCATTERER

Multiple Coulomb scattering of a charged particle beam traversing a thin scatterer results in an accumulation of small angle deflections. For one traversal of a thin scattering element of thickness x, the overall RMS scattering angle is:

$$\theta_{MC} = \frac{0.0316}{\beta_r pc}\sqrt{\frac{x}{L_{rad}}}\left(1+0.038\ln\frac{x}{L_{rad}}\right)$$

where p in GeV is the momentum, β_r the velocity and L_{rad} is the radiation length of the material, taken as 0.0705 m. For the beta-function value β at the foil, the normalised emittance blow up is then:

$$\Delta\varepsilon_n = \frac{\beta}{2}\beta_r\gamma_r\langle\theta_{MC}\rangle^2$$

MEASUREMENT OF EMITTANCE IN SPS-TO-LHC TRANSFER LINES

The emittance of a beam can be measured in a transfer line using three screens at dispersion-free locations if the momentum spread is known, and from four screens if the momentum spread is not known [2]. If the dispersion is non-zero then the dispersion function at the screen locations needs to be accurately known, to be able to determine the betatron contribution to the beam size. The dispersion in the TI 2 line is well understood [3] and, although measurement of the dispersion at the exact screen locations has been made in the past, the standard optical model was considered good enough.

The emittances were measured using four Ti screens up- and downstream of the thick Al_2O_3 screens to be used as scatterers, as illustrated in Figure 1. The Screen Matching application was used to calculate the emittances on each shot, from 2D fits to the measured profiles. A typical screenshot is shown in Figure 2.

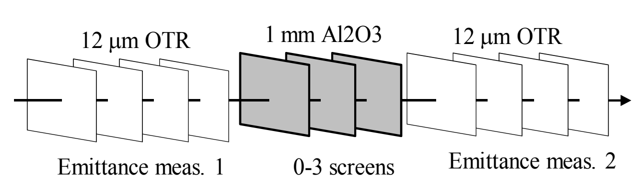

Figure 1: Schematic of the measurement using a total of 11 screens (2×4 for emittance measurement, and 0-3 for scattering the beam).

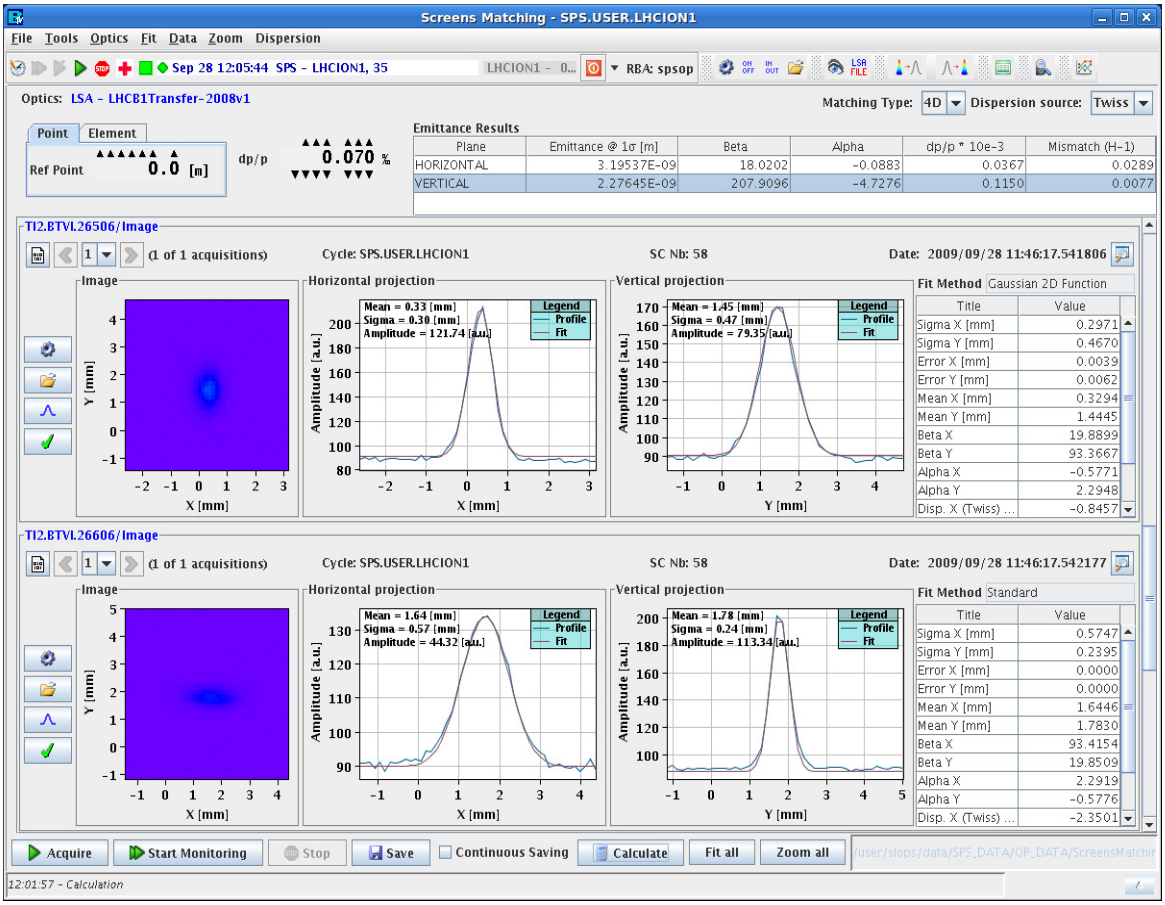

Figure 2: Image from the ScreenMatching application used to measure the emittances in TI 2 with Pb^{82+} ions. The dp can either be specified or fitted from the data.

MEASUREMENT RESULTS

Pb^{82+} Results

The Pb^{82+} measurements were made in September 2009, when ions were transported to the end of the SPS-to-LHC transfer lines. Measurements were made with 0, 1, 2 and 3 Al_2O_3 screens in place, specifically the screens in half-cells 244, 246 and 247. The filters and gains for the OTR screens were all adjusted to give unsaturated profiles, and the emittance of the beam measured in the line was about 5 nm horizontally and 3 nm vertically, corresponding to normalised emittance values of 0.9 and 0.6 µm, respectively.

With all three Al_2O_3 the screens in place the emittances increased to about 7 and 4.5 nm. The emittance increase as a function of number of Al_2O_3 screens in the beam is shown in Figure 3, together with the emittance growth expected from the simple scattering formula. The emittance change is calculated from the difference between the downstream and upstream measurement, subtracting any offset which was found with no screens.

Interestingly, the plot shows that in the vertical plane the results are rather consistent with the expectations, although the measured emittance actually appears to *decrease* after scattering through one or two screens, whilst in the horizontal plane the measured increases are 60 % larger than scattering theory predicts. The qualitative expectations from the theory are followed, with larger increases at locations with large beta function, and vice-versa.

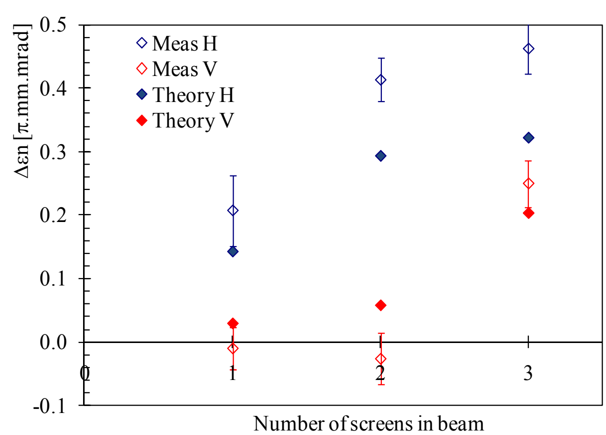

Figure 3: Normalised emittance growth of 177 GeV/u Pb^{82+} ions from 1.4 mm thick alumina screens in TI 2, compared to expectation from simple theory.

The data were also examined for correlation between the emittance measured up- and downstream of the scatterers. Figure 4 shows the correlation plot for the three data sets taken in the horizontal plane with Pb^{82+} ions. The expected correlation is evident.

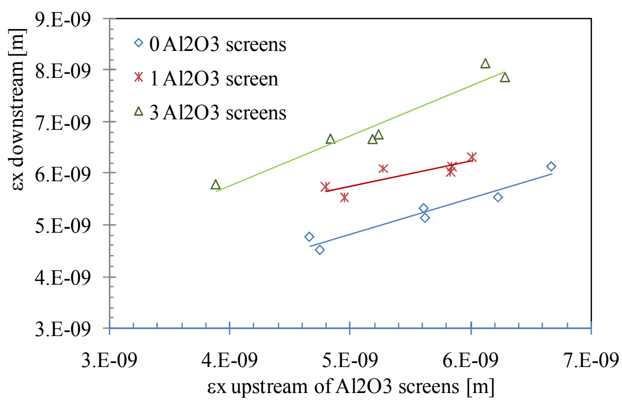

Figure 4: Correlation plot showing how the horizontal Pb^{82+} emittance measured downstream of the scatterers depends on the emittance upstream, over a number of measurement points.

Proton Results

The p+ measurements were made in May 2010. Measurements were made with 0, 1 and 3 Al_2O_3 screens in place, again for half-cells 244, 246 and 247. As for Pb^{82+} ions the filters and gains for the OTR screens were all adjusted to give unsaturated profiles. The emittance of the beam measured in the line was about 5 nm horizontally and 2 nm vertically, corresponding to normalised values of 2.5 and 1 µm, respectively.

With all three Al_2O_3 the screens the emittances were 7.5 and 3.5 nm. The emittance increase is shown in Figure 5, together with the emittance growth expected from the simple scattering formula. Again the emittance change is calculated from the difference between the downstream and upstream measurement, subtracting the offset found with no screen. No data were taken with 2 screens.

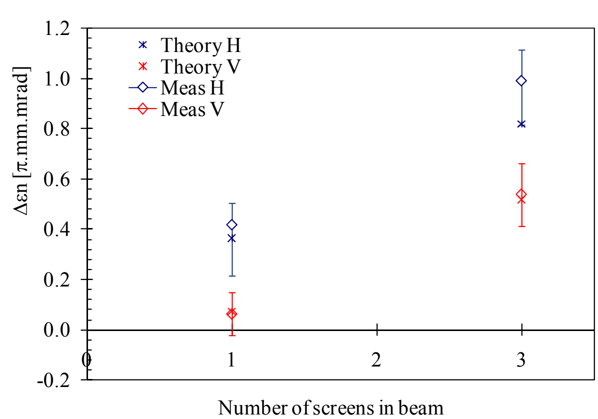

Figure 5: Normalised emittance growth of 450 GeV p+ ions from 1.4 mm thick alumina screens in TI 2, and expectation from simple theory.

For p+ the measured results agree rather well with the expectations in both planes. The error bars are larger than for the Pb^{82+} results, which was evident from the data, where not all of the measurements converged to give an emittance.

DISCUSSION AND CONCLUSIONS

The measurement technique was sensitive to the small emittance increases which resulted from insertion of the Al_2O_3 screens, and allowed a quantitative comparison with theory of the emittance increase obtained from thin scatterers. The data displayed the expected correlation between the emittance measured up- and downstream of the scatterers. The sensitivity of the method is estimated at better than 0.1-0.2 µm normalised, which could certainly be improved a factor of at least 2, by averaging over more data points. The measurement of the emittance using four screens is still sensitive to variations in dp of the beam; this could possibly be improved by reading the measured value for each shot.

The results for p+ agree well with the scattering theory in both planes. For Pb^{82+} the emittance growth in the horizontal plane is larger than expected, by about 60%. This could be due to the fragmentation of the Pb^{82+} ions and the subsequent dispersive spread, which would produce a larger than expected sigma measured in the downstream section. The dispersion in the horizontal plane at the scattering and the measurement screens is not systematically zero, and it might be possible to devise a measurement to test this hypothesis, by using a subset of the screens with zero or high dispersion to scatter the Pb^{82+} beam. In addition, the high sensitivity of this method might be suitable for benchmarking in a simple, single pass way some of the nuclear simulation codes for Pb^{82+} ion interactions with matter, which might find application in the design and analysis of ion collimation systems.

In the future the experiments could also be extended by adding specific scattering material into the beam, although this would require modification of the BTV systems and might not be compatible with normal operation.

REFERENCES

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