# EVALUATION OF EMITTANCE MEASUREMENTS FOR THE COMET ACCEPTANCE TESTS

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*Different methods to measure the emittance of a 250 MeV proton beam are evaluated for their possible use in the acceptance tests of the COMET cyclotron for PROSCAN.*

## INTRODUCTION

The specification of the beam emittance for the new super conducting cyclotron COMET is that the ellipse enclosing 90 % of the particles, should be smaller than 2π mm.mrad.

Here we report on a theoretical and an experimental comparison of several common types of measurements, to evaluate the accuracy and convenience for the acceptance tests of COMET and for later use in the PROSCAN facility.

## EMITTANCE-MEASUREMENT METHODS

We have compared the methods using a “moving slit”, “three profile monitors” and the method with the “varying quadrupole”.

The advantage of the “moving slit” method is that it yields the shape and filling of the phase space filled by the beam. A non-Gaussian filling of the phase space and/or deviations from the ellipsoidal shape are easily observed. The slit opening, however, must be rather small (<0.5 mm) to obtain a reasonable accuracy. This will be a problem at COMET’s proton energy of 250 MeV. Due to multiple scattering in the slit jaws many particles will change direction, making the results highly inaccurate.

When the beam size is measured at different positions along the beam line, one can calculate the three ellipse defining parameters at any location along the beam line. Already with three profile monitors a reasonable accuracy can be obtained. In PROSCAN, however, the expected small value of the beam emittance requires rather big distances (1-2 m) between the harps to obtain sufficient accuracy. This space is not available, however.

The emittance can also be derived from a series of beam profiles, measured with different settings of a preceding quadrupole. Simulations showed that this method is expected to be sufficiently reliable for our purpose. An important condition on the emittance to obtain sufficient accuracy, however, is that the correlation coefficient |*r*| at the entrance of the quadrupole is smaller than ~0.85. For larger values of |*r*|, the value of the ellipse area becomes extremely sensitive to small measurement errors. Although a small value of |*r*| at a quadrupole entrance does normally not occur in a standard beam optics setting, it can be achieved easily when a quadrupole triplet is used (see Fig. 1). The beam ellipse can be adjusted to a desired orientation with the first and second quadrupole and the third quadrupole is the one that is varied.

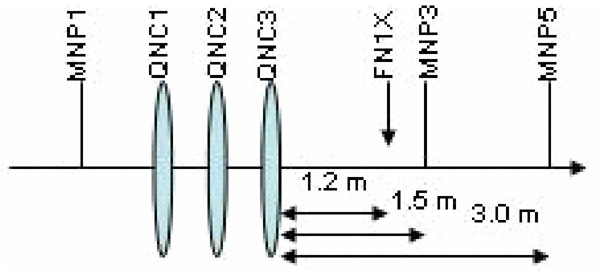


**Fig. 1:** Inj.-1 Beam line, used for the measurements

## METHODS AND MATERIALS

Emittance measurements were done in the horizontal plane with 71 MeV protons at the beam line from Injector-1. The beam intensity was typically 300-500 nA. The beam line has a triplet (QNC1, 2, and 3) followed by a set of profile monitors (MNP3 and 5).

Using profile monitor MNP1, which is located before the triplet, we were also able to perform a measurement with the “three profile-monitors” method using the envelope-fit option provided in the TRANSPORT beam optics code. Furthermore the slit FN1X and MNP5 were used for a measurement with the “moving slit” method.

With the “varying quadrupole”, one measures beam width as a function of the preceding quadrupole strength. Using the TRANSPORT notation, the square of the beam width at the profile monitor, $\sigma_{11}^{P}$, is:

$$\sigma_{11}^{P} = R_{11}^{2} \cdot \sigma_{11} + 2R_{11}R_{12}\sigma_{12} + R_{12}^{2} \cdot \sigma_{22} \qquad (1)$$

where $\sigma_{11}$, $\sigma_{12}$ and $\sigma_{22}$ are the ellipse parameters just before the quadrupole. $R_{11}$ and $R_{12}$ are TRANSPORT matrix-elements between the quadrupole entrance and the profile monitor, so they are a function of the quadrupole strength. The measured data (see for example Fig. 3) can be fitted with equation (1), using the ellipse parameters before the quadrupole as fit parameters. An accuracy estimation of these fit parameters has been calculated in the Levenberg-Marquard fitting method and verified by a Monte Carlo simulation, by assuming a 0.1 mm random error in the profile-width determination. First measurements were done manually and later by means of the control-system application SCAN (takes typically 2 minutes).

| Fit parameter | Moving slit | 3 profiles | Var Q (MNP3) | Var Q (MNP5) |
|---|---|---|---|---|
| $x_{max}=\sqrt{\sigma_{11}}$ (mm, 2 sigma) | 4.0 | 2.32 ± 0.12 | 2.44 ± 0.08 | 2.72 ± 0.04 |
| $\theta_{max}=\sqrt{\sigma_{22}}$ (mrad, 2 sigma) | 1.5 | 1.80 ± 0.10 | 1.30 ± 0.02 | 1.10 ± 0.01 |
| $r$ | 0.61 | -0.24 ± 0.04 | 0.06 ± 0.01 | 0.19 ± 0.01 |
| $\varepsilon_{90}$ ($\pi$.mm.mrad) | 4.6 ± 0.5 | 3.76 ± 0.12 | 3.16 ± 0.07 | 2.46 ± 0.03 |
| Syst. error in $\varepsilon_{90}$ | | ± 1.0 | ± 0.9 | ± 0.5 |

**Table 1**: Results of the emittance measurements ($\varepsilon_{90}$ includes 90 % of the intensity) at Injector-1, obtained by three different methods. Quoted errors are statistical errors (1 sd). The bottom row shows the estimated systematical error due to a systematic error of 0.5 mm in the profile-width determination.

## RESULTS

The measurements with a moving slit, (aperture = 1 mm) yield an emittance of $\varepsilon_{90}$=4.6 $\pi$ mm.mrad. The accuracy is dominated by the systematic errors due to the finite slit aperture and the area calculation method. The phase-space plot (Fig. 2) shows a more or less Gaussian filled, but slightly banana shaped emittance.

The measurement with the three profile monitors yields $\varepsilon_{90}$=3.8 $\pi$ mm.mrad.

In Fig. 3 a typical result is shown for a series of measurements with the varying quadrupole method. Measurements were done manually first and later by means of the control-system application SCAN (takes typically 2 minutes). We found that the results taken with SCAN did not derrate significantly from those taken manually.

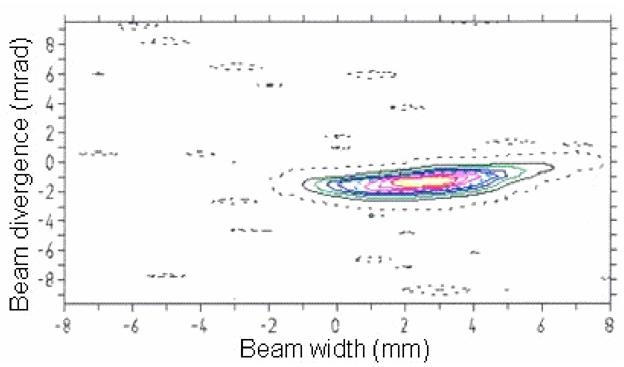


**Fig. 2:** Emittance as measured with a 1 mm wide slit.

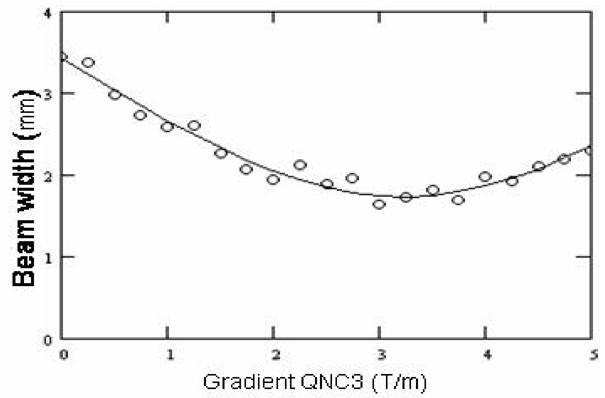


**Fig. 3:** Beam width as a function of QNC3 strength and fit of eq. (1).

Two measurements with the varying quadrupole method were performed simultaneously, by using data from MNP3 as well as from MNP5. The results of both measurements are given in Table 1.

## DISCUSSION AND CONCLUSION

The ellipse orientation found is not equal for the three measuring methods due to differences in the used optics.

The variation of the emittance values between the different methods is mainly due to fluctuations of the beam emittance in time, since the beam stability was not optimized for this experiment. However, the fluctuations are sufficiently small to get an insight in the usefulness of the different methods.

The method of the varying quadrupole showed a very small statistical uncertainty, but a scan with at least 20-30 profiles at different quadrupole settings is needed to obtain such an accuracy. The advantage of a large number of profiles is also that one can use a bootstrap method to estimate the accuracy of the fitted parameters. In such a method one randomly selects a big fraction of the data points and performs the fit with the selected data. Using several (>10) of these random data selections, the estimate of the accuracy is obtained from the spread in the values of the fit parameters.

The difference between the measurements with MNP3 and MNP5 is due to the non-Gaussian filling of the phase space. This results in an asymmetric profile, which causes a systematic error of typically 0.5 mm in the determination of the peak width. Simulations show that this effect is most severe (25 %) for MNP3, the monitor closest to the quadrupole. Due to the same type of error, the systematic uncertainty in the method with the 3 profiles is also of this order of magnitude.

For an oddly filled phase space, these last two methods allow the extension to a tomographic back projection, which shows the real shape and filling of the phase space. However, the profiles must be measured with a higher spatial accuracy than the one obtainable with the planned standard beam-profile monitors.

We conclude that the chosen method of the varying quadrupole satisfies our needs for the acceptance tests and later use, provided we take care of the analysis of non-Gaussian beam profiles.