COSY EXTRACTION LINE CHARACTERIZATION AND MODELING

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Abstract

COSY is a versatile racetrack-type synchrotron accelerating protons and deuterons in a range of rigidity between 1 Tm and 11 Tm. Circulating beam can be slowly extracted on a third order resonance and channeled towards different users. New users of the COSY beam have presented new challenges with specific requests, most notably in term of beam shape. This in turn drove a strong interest to develop and improve characterization and modeling methods in the COSY extraction beam line. In this contribution we will present the different beam characterization methods used and their limitations. We will then discuss the modeling of the line and the importance of an accurate and reliable model of the extraction line. Some of the latest beam measurements are presented and compared to modeled results.

INTRODUCTION

The synchrotron and storage ring COSY [1] accelerates and stores unpolarized and polarized proton or deuteron beams in the momentum range between 0.3 GeV/c and 3.65 GeV/c. COSY has a racetrack design with two 180 degree arc sections connected by 40 m long straight sections. It is operated as cooler storage ring with internal targets or with an extracted beam. Beam cooling, i.e. reducing the momentum spread of the beam and shrinking the transverse equilibrium phase space, is realized by an 100 keV electron cooling up to proton beam momenta of 0.6 GeV/c, by stochastic cooling for proton momenta above 1.5 GeV/c. In recent years a second electron cooler designed to operate at e-energies of up to 2 MeV and thus covering the whole energy range of the facility was added. The facility includes three external experimental stations to which the beam is guided through a beam line with conventional dipole and quadrupole magnets. The COSY beam is slowly extracted from the storage ring on a third order betatron resonance. Recently new users at the experimental stations have presented new challenges with specific requests, most notably in term of beam sizes and shapes.

EXTRACTION BEAM LINE

Figure 1 shows a floor plan of the extraction line towards one of the external experimental stations that was used for the study presented in this report. It starts with two extraction septa deflecting the beam by 5 degree each out of the COSY storage ring. The bending magnets along the line are also adjusted to provide a given deflection. Two types of normal conducting combined function dipoles with 14 and 16 degree beam deflection and corresponding quadrupole strength of 0.168 and 0.2135 m^{-1} are used. For adjustments of the beam line optics several normal conducting quadrupoles (Q11-Q22) are installed along the line. At the time of our study two of them (Q13, Q14) where powered from one common power supply, all other quadrupoles use a dedicated power supply. Multiwire proportional chambers (MW11 - MW22) with 64 wires for both horizontal and vertical planes with a wire distance of 1 mm can be moved into the beam to measure beam profiles. Table 1 summarizes the magnetic properties of the quadrupoles along the beam line.

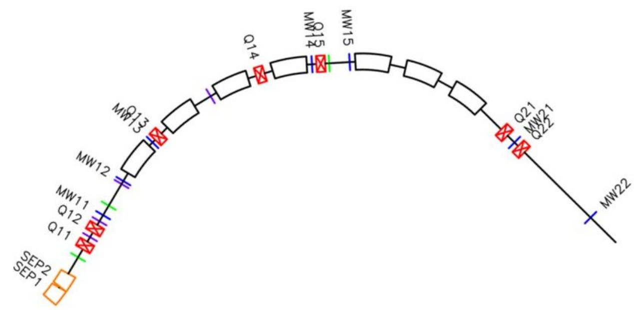

Figure 1: Floor plan of the extraction line under investigation.

BEAM PROPERTIES FROM MEASUREMENT

Slow extraction on the third order resonance is used on the COSY ring to extract the beam. Therefore beam properties in the plane of the extraction do not relate to those of the circulating beam. The beam is here extracted on the horizontal plane and we will necessarily have to start by measuring the beam properties inside the extraction line. An interesting method of beam characterisation that can be used in a single pass system is the quadrupole tune method [2]. The beam sigma matrix from the statistical definition of the emittance

Table 1: Parameters of the Quadrupole Magnets in the Beam Line

Name	s(m)	Max pole tip (T)	max grad (Tm^{-1})
Q11	4.33	0.451	9.02
Q12	5.55	0.695	13.9
Q13	12.57	0.2941	8.4029
Q14	20.12	0.2941	8.4029
Q15	23.97	0.404	11.543
Q21	36.79	0.685	19.857
Q22	38.27	0.695	19.857

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ϵ and for a Gaussian beam is

$$\Sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} < x^2 > & < xx' > \\ < xx' > & < x'^2 > \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \tag{1}$$

where x and x' are the phase space coordinates in the transverse plane considered and α, β and γ are the Twiss parameters in this same plane. We measure the beam size behind a quadrupole just separated by a drift space. The measuring device is here a multi-wire proportional chamber, measuring a projection of the beam in the plane considered. The transfer matrix M from the entrance of the quadrupole with focusing strength k to the plane of the multi wirechamber is then composed by a simple quadrupole transfer matrix and the following drift from quadrupole to wirechamber. When using the approximation for a thin quadrupole lens the transformation of the beam Sigma Matrix Σ from the entrance of the quadrupole to the wirechamber ($\Sigma^f = M\Sigma M^T$) then yields

$$\sigma_{11}^f = \sigma_{11}L^2(kl)^2 + (2\sigma_{12}L^2 + 2\sigma_{11}L)(\pm kl) + \sigma_{22}L^2 + 2\sigma_{12}L + \sigma_{11} \tag{2}$$

We can see that this equation is a second order polynomial on the quadrupole strength k . It is therefore possible to vary the quadrupole strength while recording the beam size at the multiwire chamber σ_{11}^f and a fit gives access to the beam parameters at the entrance of the quadrupole. Due to the experimental conditions in the extraction line the thin lens approximation was not accurate enough. Large gradient and low beam rigidity strongly played against the use of the thin lens approximation. Therefore we have used a fitting of the beam parameters on the measured beam size as a function of the quadrupole strength using the transfer matrix of a thick quadrupole.

MEASUREMENT AND ANALYSIS

Multiwire data are recorded for one or two extraction cycles. The quadrupole is then varied and the measurement repeated until the whole range of quadrupole strength values has been scanned. The analysis procedure is handled by a python script. The acquisition system is ran continuously such that the output data takes the form of a temporal list of measured profiles, each resulting from an integration time of around 200 ms. Then each profile from a single extraction, lasting approximately 1 s , are summed to obtain the average profile of the extracted beam. The integrated charge for each wire is coded from 0 to 255 and seldom were they saturated so we just did not consider any special case for when some channels saturate. Figures 2 and 3 show a vertical respectively horizontal profile. We use a double Gaussian fit on some of the profiles, based on the reduced χ^2 associated to each fit. There does not seem to be strong theoretical justification for a double Gaussian profile but its need is obvious to describe the measured data (see Fig. 3). The choice of a Gaussian fit for the horizontal beam profile is disputable because of the extraction mechanism but no better options were brought up, and χ^2 of the fit are reasonable. Finally, the measured profiles can be plotted as a function of the quadrupole strength and fitted to a second order polynomial from the prediction as shown in Fig. 4. It should be noted that the minimum of this curve needs to be measured to limit the uncertainty in the fitted parameters and most specifically on the fitted beam emittance.

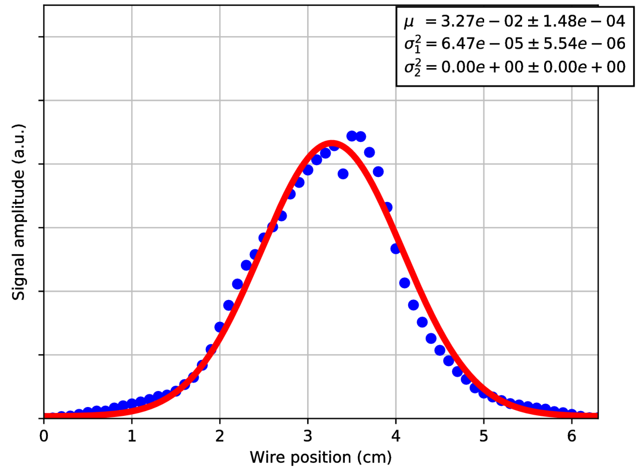

Figure 2: Typical result for vertical profile measurements (blue dots) and fit (red) for determination of width.

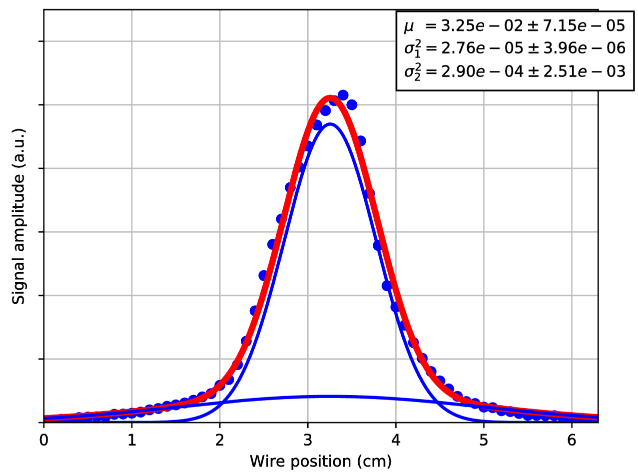

Figure 3: Typical result for horizontal profile measurements (blue dots) and fit (red) for determination of width. This illustrates the need for a double gaussian fit to accurately describe the data.

Table 2 summarizes the results for the beam parameters obtained from measurements at MW11 and MW12 for variations of Q11 and Q12. These results serve as starting beam parameters for the beam line model calculations described in the following section.

MODEL AND RESULTS

We use here the Bmad code [3] to simulate the extraction line. We have started from available MAD input files de-

Table 2: Fitted Emittance ϵ and Beam Twiss Parameters α, β for x and y Plane

Quad	MW	α_x	β_x	ϵ_x	α_y	β_y	ϵ_y
Q11	MW11	0.163 ± 0.014	8.28 ± 0.06	1.23 ± 0.01	0.315 ± 0.010	6.52 ± 0.05	4.40 ± 0.03
Q11	MW12	0.277 ± 0.017	13.35 ± 0.16	0.70 ± 0.01	0.362 ± 0.006	6.07 ± 0.06	4.09 ± 0.02
Q12	MW11	0.045 ± 0.016	3.81 ± 0.04	2.78 ± 0.03	0.321 ± 0.010	5.93 ± 0.05	5.56 ± 0.04
Q12	MW12	0.270 ± 0.015	10.65 ± 0.15	0.87 ± 0.01	0.604 ± 0.010	7.58 ± 0.08	4.02 ± 0.04

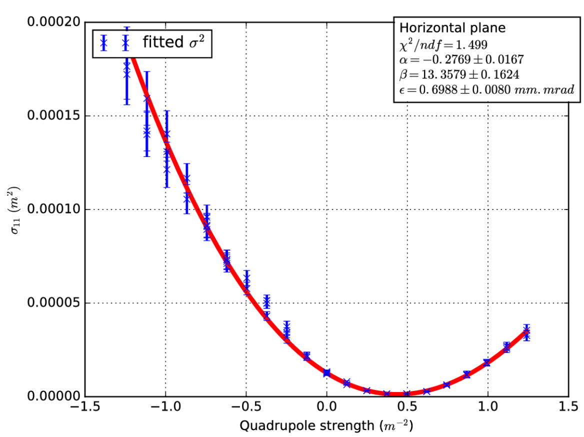

Figure 4: Typical example for beam width σ_{11} from the Gaussian fits versus quadrupole strength.

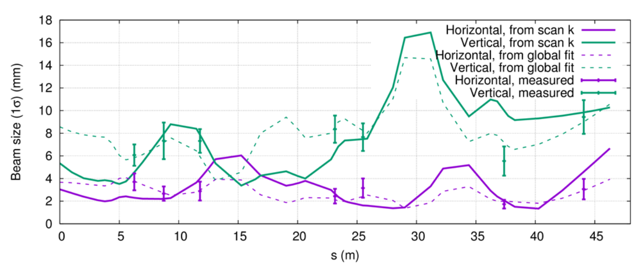

Figure 5: Comparison of the horizontal and vertical beam size calculated using the scan k method as input or a global fit in comparison to the measurement results for the different MW's.

scribing the lattice. Dipole correctors were manually added from data present in the COSY database. The extraction line is defined as starting from the upstream magnetic edge of the first magnetic septum. We have used the original drawings of the extraction line, with magnets and vacuum chamber positions, to generate an accurate model. As input to the line the beam properties determined from the measurements (Table 2) are used as input to the model calculations. As the measured beam parameters show rather large uncertainties, in an alternative approach we use a global fit to all measured profiles along the beam line (all MW data) to get an alternative presentation of the beam optics. Figure 5 shows the beam sizes computed by the two methods along with the results from the MW measurements. Possible improvements of the beam line settings, especially aiming at a reduced beam size at the experimental station (behind MW22) was

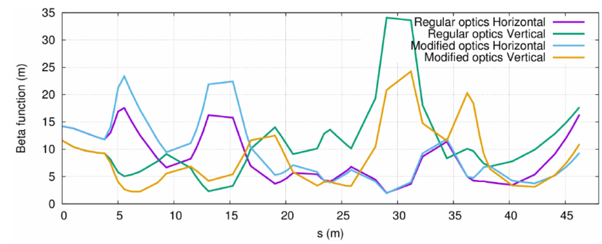

Figure 6: Comparison of the horizontal and vertical beta functions along the line as predicted by the MOGA optimization compared to the used regular beam line optics.

investigated by application of a Multi Objective Generic Algorithm (MOGA) using the DEAP python package. Figure 6 shows the resulting beta functions along the line in comparison to the presently used settings. These results look promising, beam sizes at the experiment (at s ≈ 45m) could be reduced significantly without significant increase of beam size along the line. Alternative installation of additional quadrupole magnets close to the target point was also considered, but only minor benefit was found. In view of the limited available space this solution will not be pursued.

OUTLOOK

To provide more flexibility in the adjustment of the beam line optics, quadrupoles Q13 and Q14 which were powered by a common power supply during our study are meanwhile separated and can be adjusted independently.The MW data acquisition system was upgraded by a triggered mode simplifying the assignment of acquired data to the used machine setup for future measurements. The improved optics settings predicted by the MOGA calculation presented in this report was up to now not applied and will be tested in one of the upcoming experiments. As the three existing beam lines are equipped with different quadrupole setups for the final focusing, a more careful selection of the location of experiments with respect to their requirements on beam properties will be executed in the future.

REFERENCES

[1] R. Maier, Nucl. Instrum. Meth. A, vol. 390, p. 1, 1997, doi:10.1016/S0168-9002(97)00324-0

[2] S.Y. Lee, *Accelerator physics, Singapore: World Scientific*, 2004.

[3] D. Sagan, *Bmad Reference Manual*, Cornell University, USA, 2017.