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SYNCHROTRON EMITTANCE ANALYSIS PROCEDURE AT MedAustron

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Abstract

MedAustron is a synchrotron based medical accelerator facility for particle therapy providing protons and carbon ions with clinical energies from 60 MeV to 250 MeV and 120 MeV/n to 400 MeV/n respectively. The facility features four irradiation rooms, three of which are dedicated to clinical operation and a fourth one to non-clinical research. Commissioning of all fixed lines has been completed for protons, while the commissioning for carbon ions and a proton gantry is ongoing.

For the commissioning of carbon ions, precise measurements of the transverse beam emittance in the synchrotron are of importance, to minimize beam losses and to correct for possible emittance variations due to the different clinically relevant beam intensities defined by a degrader at the end of the Linac.

The transverse beam emittance in the MedAustron synchrotron is measured via scraping at non-dispersive regions of the ring. The analysis procedure as well as emittance reconstruction accuracy for simulated data will be described in this paper, together with measurement results from the carbon commissioning.

INTRODUCTION

MedAustron is a synchrotron based ion therapy and research center located in Wr. Neustadt, Austria. Its design is based on PIMMS [1] and CNAO [2]. It features three ECR ion sources, a 400 keV/n RFQ and a 7 MeV/n IH Drift tube LINAC feeding the beam into a synchrotron with 77 m circumference. At the moment patient treatment with proton beams in the energy range of 62.4 MeV up to 252.7 MeV is taking place in two irradiation rooms featuring two fixed horizontal and a fixed vertical beamline [3].

During acceleration the beam is kept off-momentum and then extracted, using a betatron core slowly accelerating the beam onto a 3rd order resonance in the horizontal plane, which is generated using lattice quadrupoles and a dedicated sextupole magnet in a dispersion free region of the ring [4]. This allows a smooth extraction with spill-lengths between 0.1 s and 10 s. The off-momentum operation and the slow third order resonance extraction process require an accurate knowledge and precise measurements of the transverse emittance in the synchrotron.

The MedAustron accelerator features a so called *degrader* at the end of the Linac which is used to limit the number of particles being injected into the ring. It is a pepper pot like device allowing to reduce the intensity to 10, 20 or 50 % of the nominal intensity.

The current transformer in the synchrotron shows a Gaussian white noise, which is independent of the signal amplitude. This results in the signal to noise ratio being approximately 10 times worse for degrader 10 % compared to nominal intensity.

Parallel to patient treatment, commissioning of the first fixed horizontal beamline with carbon ion beam is ongoing. To facilitate the carbon commissioning, the transverse synchrotron emittance analysis procedure has been refined to obtain more accurate results , higher robustness of the analysis algorithms and allow for a completely automated measurement data analysis.

DESIGN EMITTANCES

In the following the design diluted ring emittances will be listed, since those values were chosen as simulation input to determine the stability and accuracy of the analysis procedure.

The numerical values of the design emittances can be seen in Table 1, they are the same for both planes.

Table 1: Design Emittances of the MedAustron Synchrotron in π mm mrad

Protons	60 MeV/n	250 MeV/n
RMS norm. emittance	0.519	0.519
RMS geom. emittance	1.4286	0.6679
Carbon ions	**120 MeV/n**	**400 MeV/n**
RMS norm. emittance	0.7482	0.7482
RMS geom. emittance	1.4286	0.7324

EMITTANCE ANALYSIS IN THE MEDAUSTRON FRAMEWORK

The automatic analysis program for the transverse synchrotron emittance has been coded in Python 3.4 [5] as a Level 3 tool in the MedAustron Measurement Data Analysis Framework *PACMAN* [6]. The measurements are taken via a so called *Operational Application*, a dedicated software tool in the MedAustron OpApp framework [7], which takes care of the provision of measurement configuration data to the accelerator and autonomously performs the resulting beam measurements.

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MEASUREMENT PROCEDURE

Two vertical and two horizontal copper scraper plates are installed in dispersion free regions of the synchrotron. Both plates of each pair are on opposite sides of the vacuum chamber while being at the same longitudinal position. The scraper plates are moved one by one into the path of the circulating beam while measuring the beam intensity losses with a direct current transformer (CTS). The scrapers can be moved with variable speed, with the typical speed being 0.02 m/s.

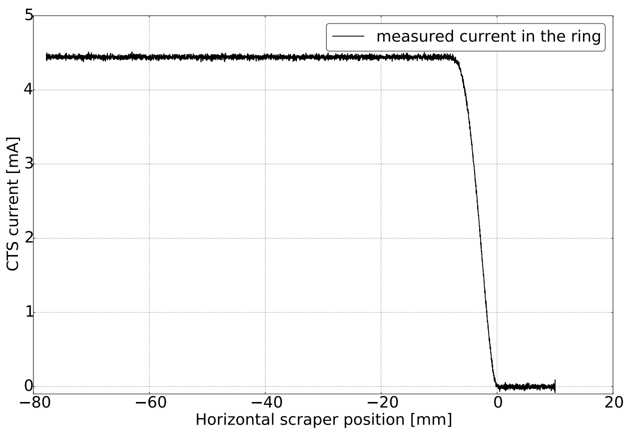

Figure 1: Measured CTS signal for a 400 MeV/n carbon ion beam with degrader 100 % at flattop when moving the horizontal scraper from negative x positions into the beam path.

ANALYSIS PROCEDURE

To calculate the emittance one can use the well known relationship:

$$\epsilon = \frac{\sigma^2_{\text{RMS,beam}}}{\beta_{\text{twiss}}} \tag{1}$$

where the β-function can be assumed from optics calculations. The RMS beam size relates to the RMS of the particle betatron amplitude distribution according to [8]:

$$\frac{\sigma^2_{\text{betatron}}}{\sigma^2_{\text{beam}}} = 2 \tag{2}$$

By calculating the numerical derivative of the signal curve shown in Fig. 1 one immediately obtains the betatron amplitude distribution of the particles as seen in Fig. 2.

Analysis Workflow

The analysis procedure follows these steps:

1. Map the beam current signal to the corresponding scraper position
2. Apply a moving average smoothing to the signal
3. Estimate the beam center

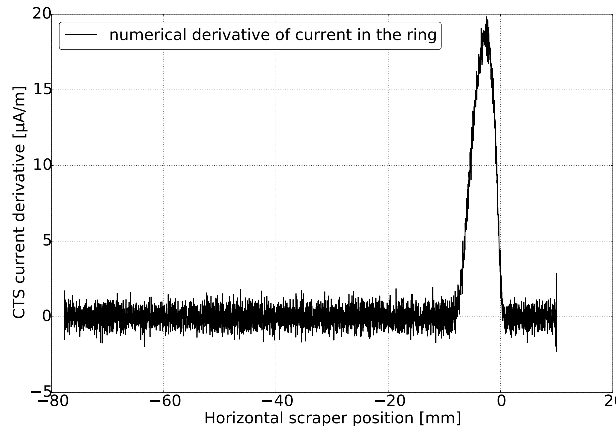

Figure 2: Numerical derivative of the signal shown in Fig. 1 after applying a moving average smoothing with a factor 50 to the signal.

4. Calculate the numerical derivative of the signal
5. Compute the RMS of the obtained betatron amplitude distribution and with Eqs. 1 and 2 calculate the geometric emittance

Estimation of the Beam Center

While a common approach to estimate the beam center is to scrape twice from opposite sides, it was a goal for this analysis procedure, to be able to create a robust possibility to calculate the transverse emittance from a single measurement as well. This has the advantages of being less prone to errors stemming from cycle-to-cycle fluctuations and allowing the usage of partially incomplete data sets. Especially the second part allows the effective use of limited shift time, as well as enabling the transverse synchrotron emittance to be measured as part of recurrent automatic quality assurance measurements, where the data analysis will be performed at a later point in time.

Multiple ways have been implemented to calculate the beam center from the CTS signal (Fig. 1):

Curve Fit If one assumes a Gaussian beam profile in a non-dispersive region, the beam current signal can be analytically described by a function of the form:

$$\frac{I(x)}{I_0} = \left(1 - \exp\left(-\frac{(x-x_0)^2}{2\beta\epsilon}\right)\right)\Theta\left(x - x_0\right) \tag{3}$$

with the Heavyside-function Θ and the center of the beam x_0. Since β and the order of magnitude of ϵ are assumed to be known, fitting Eq. 3 to the beam current signal gives quite reliable estimations of the beam center, as shown in Fig. 3. The first scraper position at which the measured current gets negative is usually a good initial value for the x_0 variable in the curve fit.

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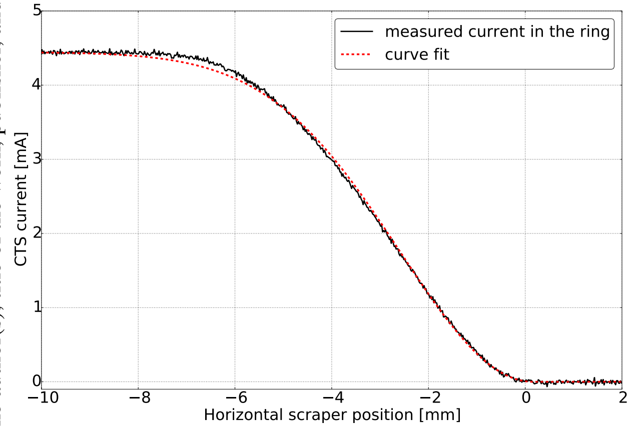

Figure 3: Function from Eq. 3 fitted to the signal from Fig. 1.

Flank Detection A more basic algorithm to compute the beam center was also implemented, which checks whether a number of consecutive points are above a threshold defined by the standard deviation of the signal noise. If that is the case the rising flank of the signal has been detected, which should coincide with the beam center.

Reconstruction of the Positional Distribution

One way to reconstruct the positional distribution of the particles from the betatron amplitude distribution is by assigning uniformly distributed angles to “particles” and modulating them with the cosine like betatron motion. The resulting distribution can give a quick optical feedback, albeit not being relevant for the emittance computation.

An example for a positional distribution calculated in this way can be seen in Fig. 4.

SIMULATIONS

The simulations to characterize the behavior of the analysis were completely done in Python 3.4. The simulation code was built directly into the analysis program and can therefore be also used as a testing tool for future releases of the whole *PACMAN* framework.

The simulations were carried out with normally distributed particles, created using the `numpy.random` module [9] with the following parameters:

Table 2: Simulation Parameters

Parameter	Value
Number of particles	10^5
Input emittance	0.66 - 1.43 π mm mrad
β (at scraper)	8.758 m
α (at scraper)	- 0.131 rads
Noise σ (degrader 10)	0.05
Noise σ (no degrader)	0.005

Accuracy of the Emittance Reconstruction without Noise

When reconstructing the transverse emittance with the parameters in Table 2, the results shown in Table 3 were obtained, showing a very good accuracy of the algorithm. For each input emittance the simulations were run 10 times.

Table 3: Relative errors in reconstruction for the ideal case simulation with no noise. Geometric emittances given in π mm mrad.

ϵ	reconstructed ϵ	relative error [%]
0.66	0.662 ± 0.005	0.35 ± 0.71
1.045	1.049 ± 0.009	0.47 ± 0.85
1.43	1.435 ± 0.009	0.38 ± 0.63

Accuracy of the Emittance Reconstruction with Varying Noise

The noise on the beam current signal is simulated as being normally distributed, with a standard deviation given in Table 2. The values for the noise standard deviation were derived from real measurement data.

Table 4: Relative errors in reconstruction for no degrader and degrader 10 %. Geometric emittances given in π mm mrad.

	ϵ	reconstructed ϵ	relative error [%]
no deg.	0.66	0.679 ± 0.006	2.81 ± 0.95
	1.045	1.069 ± 0.074	2.31 ± 0.71
	1.43	1.459 ± 0.014	2 ± 0.93
deg. 10	0.66	0.699 ± 0.031	5.97 ± 4.64
	1.045	1.071 ± 0.048	2.44 ± 4.63
	1.43	1.492 ± 0.074	4.34 ± 5.15

What can be immediately seen from the results shown in Table 4 and Fig. 5 is, that the repeatability decreases significantly with worse signal to noise ratio, while the average error does not increase as much.

MEASUREMENT RESULTS

The improved analysis procedure has already been put to use during the commissioning of carbon ions as well as in the analysis of repetitive proton quality assurance measurements.

In Table 5 measurement results for the carbon ion beam are summarized which show very good agreement with the design value of 0.7482 π mm mrad.

CONCLUSION

The improved emittance analysis procedure tool at MedAustron allows completely automatic and robust reconstruction of the transverse synchrotron emittance from scraping measurements, even when only scraping from one

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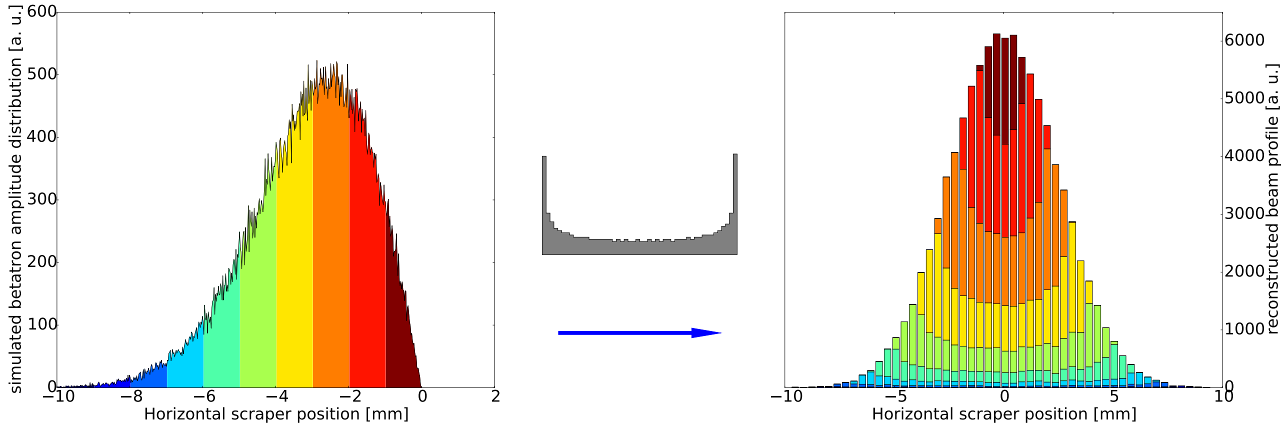

Figure 4: The betatron amplitude distribution (left) is modulated with a cosine distribution (center) to obtain the symmetrical particle position distribution (right).

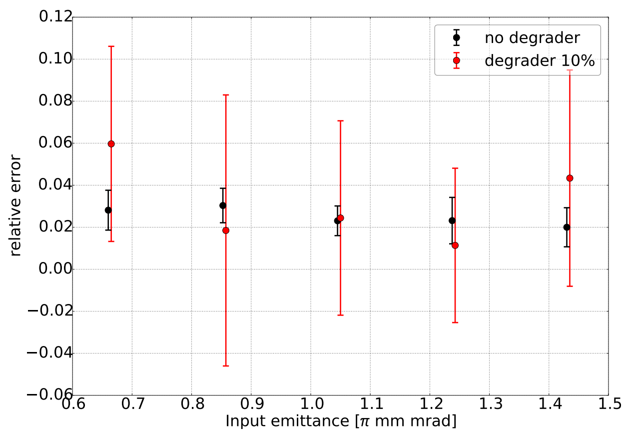

Figure 5: Relative emittance reconstruction error for two different degrader settings.

Table 5: Normalized horizontal emittance results of the still under commissioning carbon beam for the lowest and highest extraction energy in π mm mrad.

degrader	120 MeV/n	400 MeV/n
100 %	0.74	0.81
50 %	0.71	0.74
20 %	0.69	0.74
10 %	0.63	0.76

side. Simulations show that the tool can reliably reconstruct the emittance with average relative errors of less than 1 %. The analysis accuracy is at the moment strongly dependent on the relative noise level of the measured signal, which should be further investigated to mitigate the possible errors introduced. The tool has already been put to use during commissioning and repetitive quality assurance measurements and could show that the emittance for the carbon ion beam under commissioning is within 10 % of the design value.

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