BEAM MEASUREMENTS IN THE MEDAUSTRON SYNCHROTRON WITH SLOW EXTRACTION AND OFF-MOMENTUM OPERATION

C. Kurfürst*, A. De Franco, F. Farinon, M. Kronberger, S. Myalski, S. Nowak, F. Osmic, M. Pivi, C. Schmitzer, P. Urschütz, A. Wastl, EBG MedAustron, Wr. Neustadt, Austria
L. Penescu, Abstract Landscapes, Montpellier, France
T. Kulenkampff, CERN, Geneva, Switzerland
A. Garonna, TERA Foundation, Geneva, Switzerland

Abstract

The MedAustron Ion Therapy Center is a medical accelerator facility for hadron therapy cancer treatment using protons and carbon ions. The facility features 4 irradiation rooms, three of which are dedicated to clinical operation and a fourth one dedicated to non-clinical research. The latter was handed over to researchers in autumn 2016. A 7 MeV/n injector feeds a 77 m circumference synchrotron which provides beams for treatment and research. Routine verification measurements in the synchrotron involve beam emittance, dispersion as well as tunes and chromaticity. The horizontal and vertical emittance are measured using scraping plates and a direct current transformer. The dispersion function in the ring is determined by sweeping the synchrotron RF frequency while measuring the beam position in the shoebox pick-ups. The horizontal and vertical betatron tune and chromaticity are measured with Direct Diode Detection electronics, developed at CERN, while changing the beam position with the RF radial loop. The beam is kept off-momentum, thus in dispersive regions the closed orbit is largely offset from the central orbit. Methods for beam measurements in the synchrotron are presented.

INTRODUCTION

MedAustron is a synchrotron based hadron therapy and research center. Its design originates from those of PIMMS [1] and CNAO [2]. The therapy accelerator comprises three ECR ion sources feeding a 400 keV/n RFQ and a 7 MeV/n IH Drift tube linac. The facitlity provides medical proton and carbon beams in the respective energy range of 60-250 MeV/n and 120-400 MeV/n via slow resonant extraction spills. For non-clinical research purposes, proton beams with energies of up to 800 MeV/n can be provided. During acceleration, the beam is kept off-momentum, while the horizontal on-momentum tune is slowly changed to the third order resonance to prepare for the slow extraction process. The off-momentum operation and the slow third order resonance extraction process require an accurate knowledge and precise measurements of the betatron tune and the chromaticity, the transverse emittance and the dispersion in the synchrotron.

* christoph.kurfuerst@medaustron.at

TUNE AND CHROMATICITY

Due to the third order resonance extraction mechanism, the choice of the horizontal tune and chromaticity are critical. They must meet the following constraints [3]:

- The horizontal lattice tune must be placed on the 5/3 resonance. The vertical tune value is less important, as long as it is not close to major resonances.
- The chromaticity is chosen to fulfill the Hardt Condition.

Tune

The betatron tune is measured by introducing a short excitation to the beam and measuring the coherent oscillations. Subsequent analysis of the resulting beam oscillations by Fast Fourier Transform (FFT), example shown in Fig. 1, provides the fractional tune.

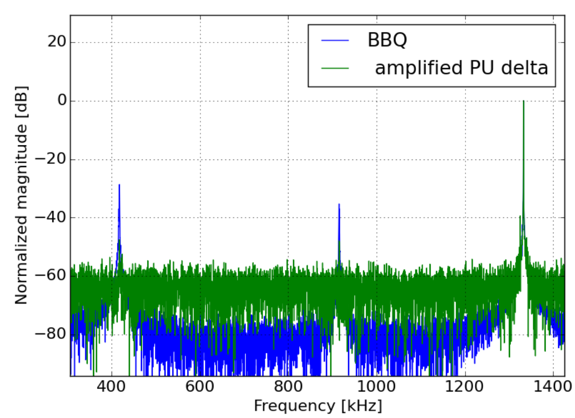

Figure 1: FFT of the shoe-box pick-up signals of the excited beam with the BBQ signal (blue curve) and the amplified pick-up Δ signal (green curve). The revolution frequency is visible, as well as two betatron sidebands.

The presented tune measurements are performed with the tune kickers and shoe-box pick-ups while the beam is bunched. All pick-ups in the synchrotron are connected to position readout electronics. In addition two pick-ups, one horizontal and one vertical, are attached to the Direct Diode Detection (3 D) electronics, which allows to increase the betatron frequency content in the baseband [4]. This 3 D measurement system will further be referred to as base band tune (BBQ). There are two kicker magnets, one for each

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plane, installed at $\beta_x = 5$ m and $\beta_y = 4.5$ m. The maximum available integrated field of the horizontal tune kicker is 8.8 mTm, which corresponds to a kick of 1.4 mrad at top magnetic rigidity ($B\rho = 6.35$ Tm). A kick of 0.03 mrad gives rise to an oscillation amplitude at the pick-ups of 0.5 mm. Due to filamentation, the orbit oscillation result in an emittance blow-up of 5% at injection and 10% at extraction. The kicker magnets perform the ramping up to and down to zero from the defined kick-strength while there is no beam inside the element. The beam is hence kicked during a single passage of the beam. The synchronisation between the beam passage and the kickers is done via the synchrotron Radio Frequency (sRF). The intrinsic precision of this tune measurement is proportional to the measurement time, which is limited by the decoherence time due to chromaticity and momentum spread.

The FFT of the shoe-box pick-up signals of the excited beam are shown in Fig. 1, once connected to the BBQ and once for comparison with the amplified Δ signal. Figure 2 is a zoom of the FFT at the betatron peak level, while Fig. 3 shows the peak at the revolution frequency. The resulting horizontal betatron tune from the plotted examples is $Q_x = 1.6867$ at a radial position of 41.7 mm in the high dispersive region.

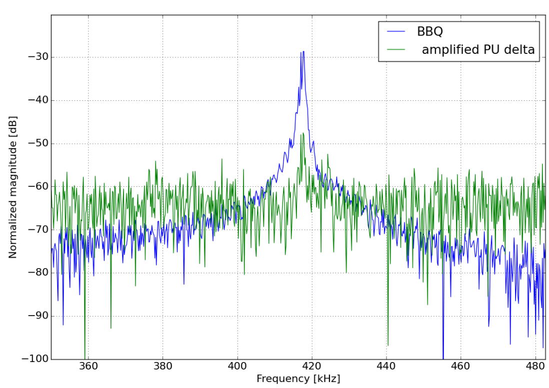

Figure 2: Horizontal betatron sideband at 62.4 MeV/n. The advantage of the BBQ system is clearly visible.

Chromaticity

The chromaticity is measured by repeated tune measurements while changing the radial position via the sRF regulation loops. The evolution of the horizontal tune for different radial positions is shown in Fig. 4. The obtained values can be transformed into δQ over δp/p, allowing the calculation of the chromaticity through the knowledge of the dispersion function in the synchrotron. The measurements resulted in a chromaticity -4.1 for 62.4 MeV/n, while the design value is -4. Further results are discussed in [5].

TRANSVERSE BEAM EMITTANCE

The transverse emittances in the ring are chosen based on the following considerations:

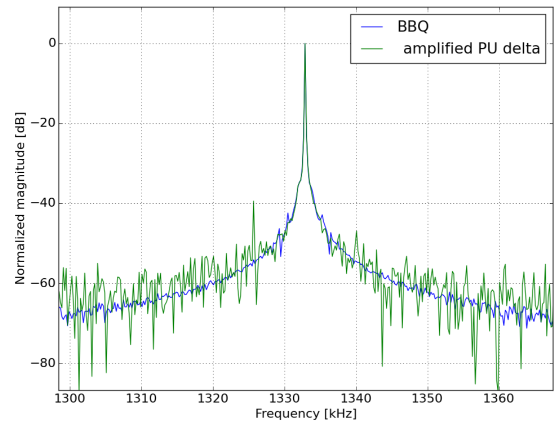

Figure 3: Revolution frequency at 62.4 MeV/n.

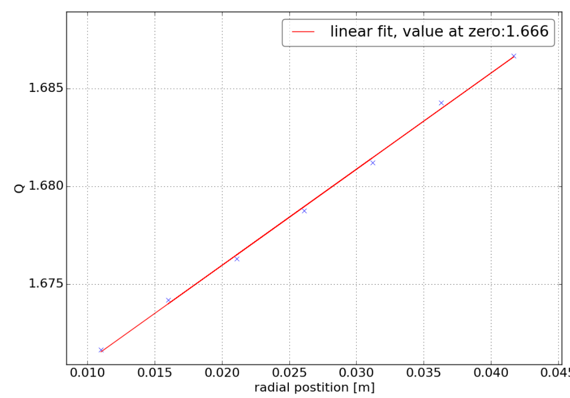

Figure 4: Tune measurements for several radial positions at 62.4 MeV/n, with a third order resonance on-momentum tune.

- The normalized vertical emittance for protons and ions is chosen such that the two species have approximately equal geometrical emittances over the full range of available extraction energies. The emittances are chosen to achieve the specified beam spot sizes at the irradiation rooms (IR) focal point: $\sqrt{5}\sigma$ = 4 to 10 mm.
- The normalized horizontal emittances in the ring map into the momentum spread of the extracted beam via the betatron core driven resonant extraction mechanism. A too large horizontal emittance therefore results in a large momentum spread of the extracted beam and in losses, but a large emittance also reduces the proton space-charge tune shift at injection.
- Transverse linac emittances are typically small and can be diluted in a controllable way to meet the above requirements.

To measure the emittance in the ring, two vertical and two horizontal copper plates (scrapers) are installed in the main ring. The pairs are at the same longitudinal position in the ring and for each pair the plates are on opposite sides of the vacuum chamber. The scrapers are moved into the beam path of the circulating beam while measuring the beam intensity losses in the synchrotron with a direct current transformer. The typical scraper speed for the measurements is 0.02 m/s. The intensity losses during the scraping procedure are shown in Fig. 5. From the loss pattern the beam profile is reconstructed, see Fig. 6. The beam emittance is calculated from the reconstructed profile throught the knowledge of the Twiss β functions at the scraper level. The results are in agreement with the design considerations.

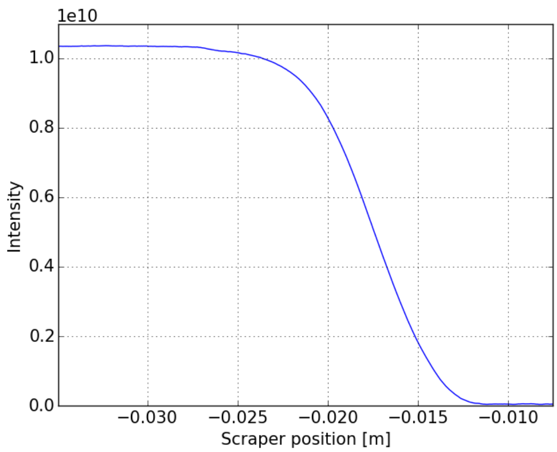

Figure 5: Intensity losses during the scraper movement in the main ring at 252.7 MeV/n for a machine configuration with 50 % of the nominal intensity.

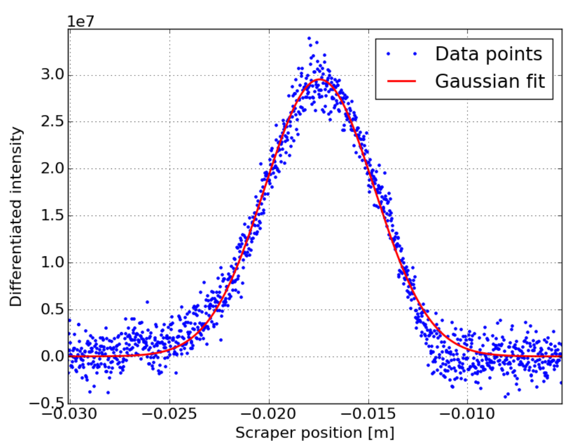

Figure 6: Reconstructed vertical profile in the main ring at 252.7 MeV/n for 50 % of the nominal intensity. The Gaussian fit results in a σ of 2.76 mm.

DISPERSION

The dispersion is measured by slightly varying the beam energy and measuring the beam positions within the pick-ups. The variations are performed by sweeping the sRF frequency to increase the beam energy and by using the sRF radial loop to control the radial beam position while keeping the synchrotron dipoles at constant strength. Figure 7 shows the outcome of such a variation, allowing to compute the dispersion as summarized in Table 1, assuming a design γ transition.

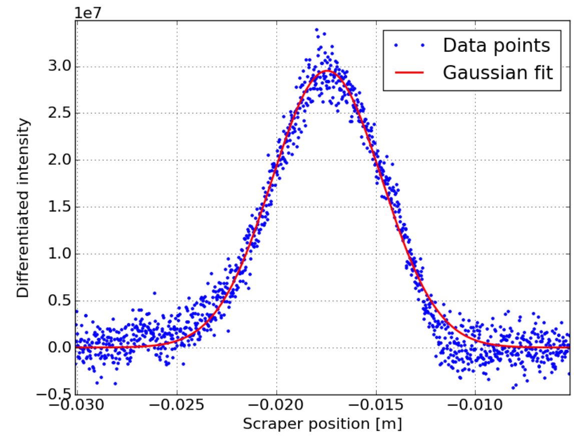

Figure 7: High dispersive region pick-up position plotted against the sRF frequency ramp at 252.7 MeV/n.

Table 1: Resulting Measured Dispersion and Comparison to Simulations From MADX

Region	MADX	Measured
non-dispersive	0	-0.1
high dispersive	-8.4	-8.4

CONCLUSION

The precise measurements of the dispersion, the transverse emittance, the betatron tune and the chromaticity in the synchrotron allowed to properly adjust the MedAustron accelerator for off-momentum operation and slow extraction via third order resonance extraction mechanism. Regular verification measurements of these parameters in the synchrotron are foreseen for quality assurance [6]. Additional effort is put into further optimization and automation of the measurement procedures via the expansion of specialized tools [7], as well as increased usage and read-out improvements of the Schottky monitor [8] for example.

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