LONGITUDINAL BEAM DYNAMICS IN THE HDSM AT MAMI*

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Abstract

The 1.5 GeV Harmonic Double Sided Microtron (HDSM) [1] as the fourth stage of the Mainz Microtron (MAMI) is now in routine operation for two and a half years [2]. Simulations predicted a wide range of applicable longitudinal parameters with which the machine can be run and measurements of the longitudinal acceptance confirmed that. The reproducibility of different configurations is good enough to support a fast and reliable set-up of the machine and to guarantee a stable long-term operation.

In order to optimize the configuration a reliable measurement of the phases and accelerating voltages in both linacs is essential.

Each turn's phase information is provided by low-Q TM_{010}-resonators at both linacs when operating the machine with 10ns diagnostic pulses (Fig. 1).

The HDSM's four bending magnets are designed with a field gradient to compensate the vertical fringe defocussing. Their decreasing field integral results in less synchronous energy gain per turn, automatically causing a change of the longitudinal phase. The calibration of the phase signals, which in case of the Race Track Microtrons (RTM) is easily done by exciting a synchrotron oscillation, was refined for the HDSM to deliver precise phase data.

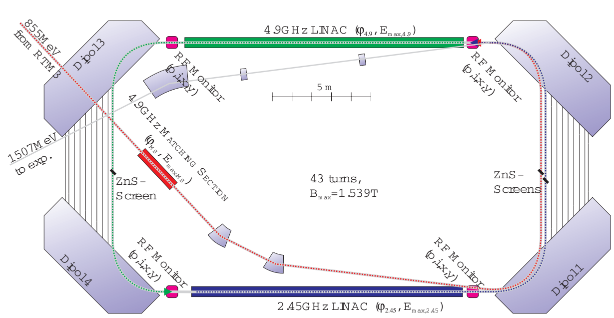

Figure 1: Scheme of the HDSM showing the relevant rf-system installations described in this article.

INTRODUCTION

Phase Analysis in a Racetrack Microtron

Till December 2006 the MAMI accelerator consisted of three cascaded racetrack microtrons.

Each of the RTM linacs is equipped with low-Q rf-resonators for monitoring. Two TM_{110}-monitors provide position information at the entrance and exit and one TM_{010}-monitor (PIMO) detects beam phase and intensity. The rf-monitor signals are demodulated by a mixer with a reference rf-signal. Turn-by-turn information is obtained by using 10 ns long high intensity diagnostic pulses, exciting the resonators anew on each recirculation (e.g. Fig. 2).

In case of the TM_{010}-monitor this reads for every turn n for the pulse heights [3]:

$$\begin{aligned} U_{phase}(n) &= U_{0,ph.} \cdot \sin\left(\varphi(n) + \varphi_{ref,ph.}\right) \\ U_{intensity}(n) &= U_{0,int.} \cdot \sin\left(\varphi(n) + \varphi_{ref,int.}\right) \end{aligned} \tag{1}$$

where $U_{0,ph.}$ and $U_{0,int.}$ depend linearly on the beam current and $\varphi(n)$ is the examined turns phase relative to the reference phase φ_{ref}. Both signals originate from the very same monitor which makes them congeneric, and only the phase difference $\varphi_{ref,int.} - \varphi_{ref,ph.}$ is chosen to be $\pm 90\,°$.

A suitable measurement then is $U_{phase}/U_{intensity}$ which eliminates the dependency on the beam intensity and leads (with $ratio = U_{0,int.}/U_{0,ph.}$) to:

$$\varphi(n) = \arctan\left(\frac{U_{phase}(n)}{U_{intensity}(n)} \cdot ratio\right) - \varphi_0 \tag{2}$$

where φ_0 is the first turn's phase.

Considering the homogeneous $180\,°$ bending magnets the energy gain per turn in a RTM is constant in first order when there are no synchrotron oscillations.

The dynamic coherence condition

$$\Delta E = \frac{e \cdot c \cdot B}{2\pi} \cdot k \cdot \lambda = \Delta E_{max} \cdot \cos(\varphi_{sync.}) \tag{3}$$

correlates the synchronous energy gain ΔE with the bending magnets' field B, the harmonic number k and the rf-wavelength λ. Stable acceleration for $k = 1$ is given for $-32.5\,° < \varphi_{sync} < 0\,°$.

Using the strong longitudinal focussing and well defined synchrotron oscillations, the phase advance per turn can easily be determined and the phase signals are then calibrated [4] resulting in $ratio$ and φ_0 in Eq. 2. This data is used to optimize the longitudinal beam parameters ΔE_{max} and φ_{sync} by adjusting the injection energy and the linac's rf-amplitude and phase to provide smooth acceleration without synchrotron oscillations at the desired longitudinal tune.

DYNAMICS IN THE HDSM

Phase Signals of the HDSM

The HDSM in contrast has $90\,°$ bending magnets with a field gradient perpendicular to the pole face, which results in less synchronous energy gain from turn to turn.

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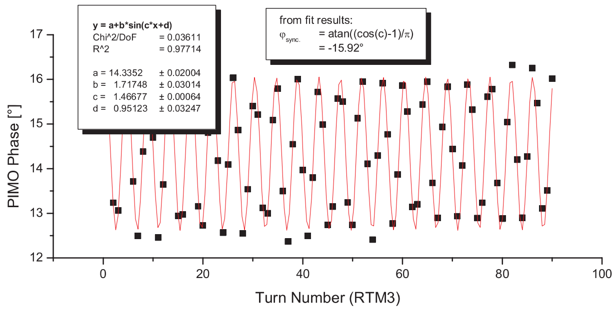

Figure 2: Beam phase signals for 90 turns in RTM3 (2 ° synchrotron oscillation amplitude). The calibration of the phase signals and the longitudinal tune are extracted from a sine-function fit.

The longitudinal focussing automatically provides the necessary change of each turn's phase, as indicated in Fig. 3. However, exciting synchrotron oscillations can not be used to calibrate the HDSM's phase signals any more, as the synchrotron frequency is not constant during the acceleration process. The calibration now depends strongly on the actual setting of the machine. Instead the phase signals have to be calibrated beforehand in order to determine the longitudinal settings.

The first difficulty was to compensate some imprecisions of the raw signals which did not deliver the expected pulse shapes. Calibrating the phase signals was almost impossible, as the detected pulse heights $U(n)$ did not fulfil Eq. 1 while varying the monitor's reference phase φ_{ref} with high precision stepmotor-driven waveguide phase shifters.

But after improving the peak detection routines the data could be calibrated for all turns of both linacs. One calibration of the 4.9 GHz linac is shown in Fig. 4. But still φ_0 is arbitrary and cannot be extracted, therefore these phase measurements provide only relative data.

Since different rf-settings (two linac amplitudes, the corresponding phases and the injection energy) can produce similar phase data, the errors of the calibration procedure alone are too large to give precise results when fitting different models to the data.

Determining First Turn's Phase φ_0

To complete the data for both linacs and also for the matching section φ_0 has to be determined accurately. First attempts using ZnS-screens for the position in the transversal dispersive arcs of the HDSM provided some experience when varying the corresponding linac's phase. Later this approach was elaborated: it utilizes the longitudinal dispersion from a linac to the following one measured with the rf-monitors (Fig. 1), and can be used automatically during routine setups. One result is shown in Fig. 5.

This tool is very useful because it allows to reproduce different longitudinal rf-settings rather easily which was much more difficult before.

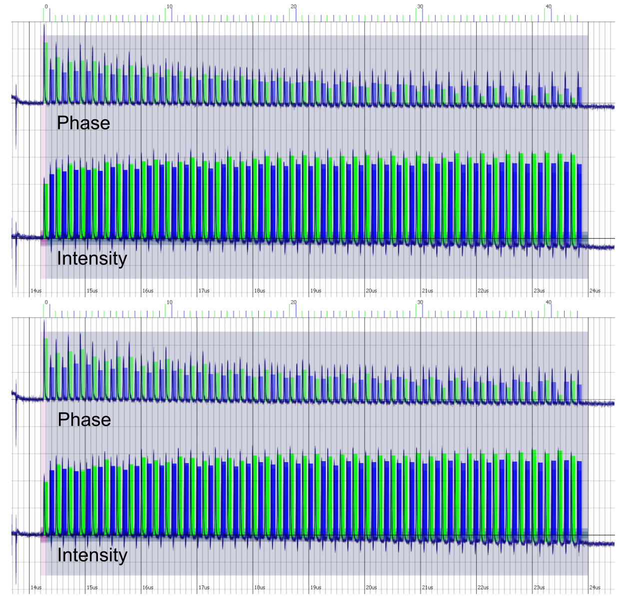

Figure 3: Phase and intensity signals of the HDSM, 4.9 GHz linac data green (even bars) and 2.45 GHz linac data blue (odd bars). The lower picture shows synchrotron oscillations of 3 ° relative to 4.9 GHz.

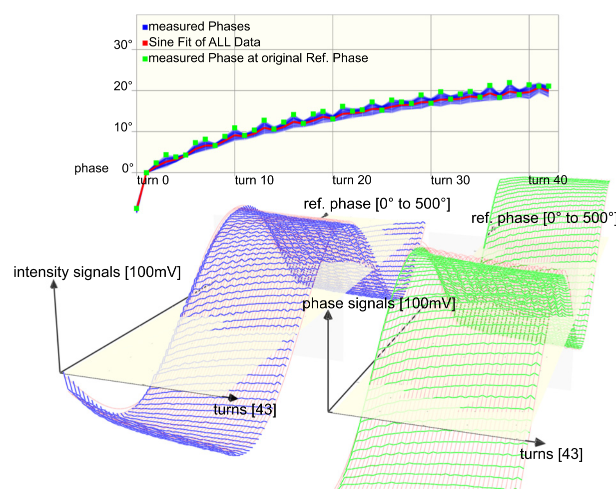

Figure 4: Calibration of the phase and intensity signals of the 4.9 GHz linac. Horizontally shown are the signals for all 43 turns, and the varied reference phase φ_{ref} points into the drawing surface. In the topright diagram the calibrated signals for all reference phase settings are superposed, the green dots show the evaluated data at standard reference phase.

APPLICATIONS AT THE HDSM

Longitudinal Acceptance

Even knowing the first turns phase may not be sufficient to accelerate the beam without any losses through all 43 turns.

Therefore a dedicated tool was developed which scans the longitudinal phase space by varying the injection en-

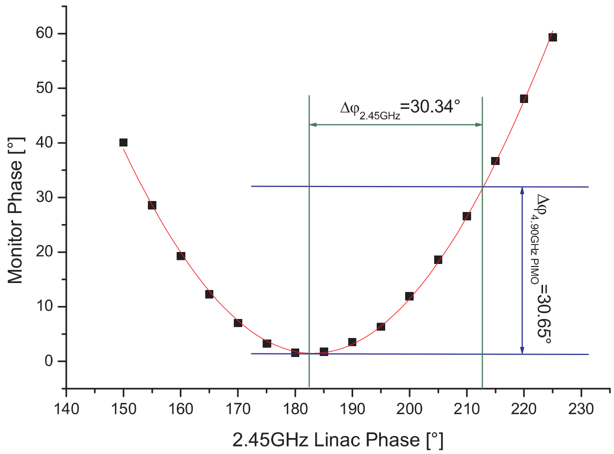

Figure 5: Determining the phase for the first turn in the 2.45 GHz Linac. The difference $\Delta\varphi_{2.45GHz}$ between linac phase for the extremum and the original arbitrary value of 212 ° is the first turn's phase φ_0.

ergy (via the matching section's phase) and the HDSM's phases. In addition both linacs can be varied in parallel and relative to the other, so in the end there are 3 phases to be optimized at any given rf-voltages. Transverse motion of the beam is not considered except for beam losses caused by the transversal dispersion in the 180 ° systems. For the simulation a ΔE_{max} of 0.5 MeV means Δx of 2 mm there and is the maximum tolerated deviation for good transmission. Besides the injected beam is centered always on the linac axis after varying the injection energy. For each point during the measurement the phase data of all turns are gathered. These data can be used to find and apply the configuration with least synchrotron oscillations and best transmission.

As there are many measured data using the same two rf-voltages and injection energy while varying only the linac and the matching section phases very precisely, the longitudinal dynamics of the HDSM can be analyzed systematically.

Figure 6 shows one measured and one simulated set of data. For the measurement the rf-voltages of the linacs were determined to be 8.9 MV at 4.9 GHz and 9.1 MV at 2.45 GHz within calibration errors of the power measurement of $\pm 5\%$. Fitting the rf-voltages individually for all the data where the beam arrived in the extraction beamline resulted in average voltages of 9.6 ± 0.6 MV and 8.5 ± 0.5 MV. These parameters were used to produce the simulated graph.

Of course different rf-voltages can result in a dramatically decreased (or increased) longitudinal acceptance. Therefore the voltage settings are retained for different experimental beam times, which makes it much easier to find optimum settings rather quickly.

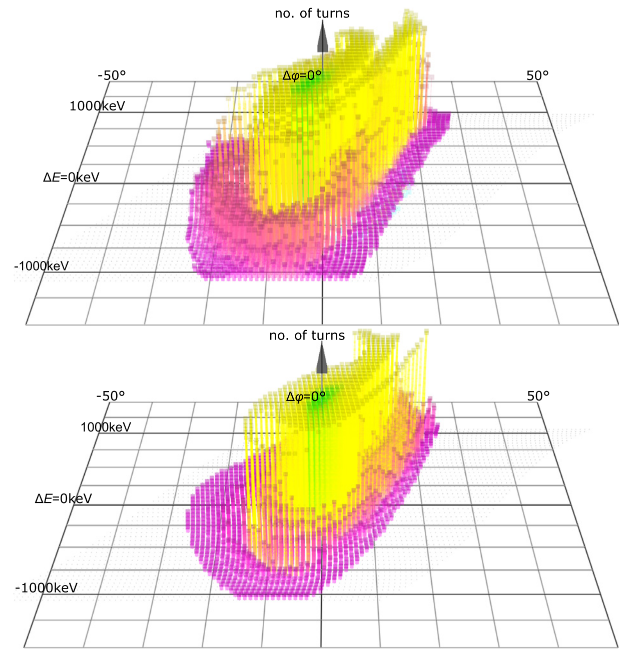

Figure 6: Measured (top) and simulated (bottom) longitudinal acceptance. The number of reached turns (max. 43) is given by the height of the bars. The green area in the center marks relatively small synchrotron oscillations whereas the yellow and red area indicate larger oscillations.

CONCLUSION

There are still improvements possible. Particularly the rf-amplitudes setting is difficult to fit, and there are some minor imperfections at the phase- and intensity signals to be fixed which reduce the phase resolution.

The longitudinal beam dynamics of a HDSM with its two linacs and five free parameters is much more complicated than in the RTM case. With the introduced analysis tools it is possible to characterize and operate the HDSM close to the longitudinal design values. Particularly during setup routines the determination of the first turns' phase has reduced the time needed to start up the HDSM.

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