COMPUTER MODELS TO OPTIMISE THE SETTING OF THE MAMI DOUBLE SIDED MICROTRON*

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Abstract

The MAMI microtron cascade has been upgraded from 0.855 to 1.5 GeV by a 4th stage. This stage – successfully in operation since February 2007 for experiments in nuclear physics and delivering a c.w. electron beam of 100uA at 1.604GeV maximum – is a worldwide unique scheme, a Harmonic Double Sided Microtron (HDSM) [1]. In contrast to a Race Track Microtron (RTM) one turn in the HDSM implies the passage of two different linac lines and accordingly two independent beam focusing systems. Due to the higher number of parameters it turns out to be much more difficult to understand and to describe the actual transverse and longitudinal beam dynamics in detail. For this reason parameterised models of the beam optics were implemented into the control system, which can be adapted, e.g. by least squares fit, to the measured beam response. The models enable analysis and fine tuning of the machine optics as well as effective correction algorithms for the rf-amplitudes and -phases of the linacs or the settings of the beam position steerers.

INTRODUCTION

MAMI is a normal conducting accelerator consisting of a pre-accelerator, three RTM stages and a HDSM (Fig. 1) as last stage. The latter is in routine operation since beginning of 2007, delivering beam for various experiments in nuclear physics. To enable the around-the-clock operation of the accelerator, it is run by students on night and weekend shifts. This requires to simplify and to automate the beam setup and optimisation procedures. Most of the automatic or semi-automatic machine tuning has been programmed in a BASIC-like language [2] by experienced staff operators. In some of these routines simple beam optical calculations are already performed. However, more complicated optimisation procedures had to be programmed in a more appropriate language (C/C++), using comprehensive models of the relevant beam optics.

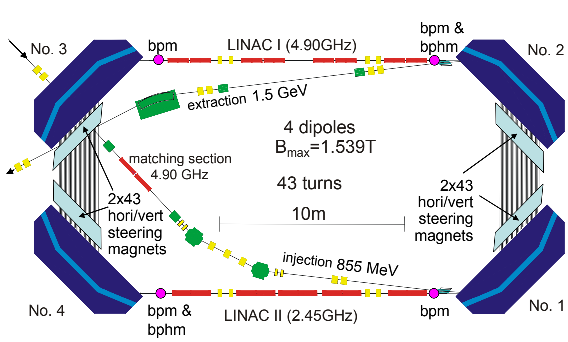

Figure 1: Layout of the HDSM.

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OPTIMISATIONS

In a microtron the beam has to be controlled in two essential manners. Firstly injection energy and phase of the beam have to be adjusted to appropriate values, depending on the magnetic field of the bending dipoles and the rf-settings. One criterion for the correct setting is that the turn by turn synchrotron oscillation, detected with beam phase rf-monitors (bphm)[3], cancels. But in a HDSM there is no simple relation yielding a parameter correction to achieve this. Secondly the transversal beam position has to be centred on the linac axis turn by turn. Thus two rf-monitors (bpm) on each linac axis provide the read-out of the beam positions and two horizontal and vertical beam steerers on each of the deflection paths enable beam centring. It is not beneficial to correct only a single turn, because this affects all subsequent turns. More favourable and much faster is to correct all turns in one step by using a model predicting induced beam position changes for as many turns as possible. An appropriate optimisation algorithm was described in [4] for the first time. The efficiency of such a correction procedure depends strongly on the quality of the model. So in both cases, longitudinal and transversal, one needs to predict the response of the beam to the change of rf parameters, respectively beam steerer settings.

MODELING AN RTM

Longitudinal

A standard RTM as operated at MAMI has homogeneous bending dipoles, so the beam phase in its linac is the same for each turn; typically it should be -16^{o}. Thus the frequency of the synchrotron oscillation is turn number independent and indicates directly the set-point of the beam phase, enabling the adjustment of the rf-amplitude in the linac. The two remaining parameters (input energy and phase) can easily be found by digging around, until the synchrotron oscillation cancels. This tuning procedure is rather simple and up to now there was no need for a more sophisticated one.

Transversal

The transversal beam optics is essentially given by the setting of the two quadrupole doublets on the linac axis and (only vertically) by the reverse field amplitudes in front of the two bending dipoles. Due to the energy dependent focusing the betatron frequency decreases nonlinearly with increasing turn number. The focusing strengths are not known accurately enough to describe the betatron oscillation with a simulation based on their intended set-points for more than some few turns. Therefore, to find a description of the beam optics, a simple simulation is adjusted to the actually measured betatron oscillations using a Levenberg-Marquardt algorithm. The resulting model is sufficient to provide for proper operation of the automatic steerer optimisation, though it does not reflect the actual settings of the quadrupoles, respectively of the reverse fields.

THE HDSM

The HDSM is a more complicated machine. Due to the special field-profile of the four bending dipoles [1] there is no constant beam phase, and due to the two linacs there is neither an easy way to find out their correct rf-amplitudes and their relative phasing, nor to fit the 4 quadrupole doublet settings and the obscure fringe field effects in the dipoles. New methods had to be found to automate beam optimisation. In longitudinal direction a more phenomenological approach was chosen by scanning the phase space using the rf-phase shifters to get a tomogram of the phase space acceptance. In the transversal planes a more sophisticated model of the HDSM beam optics has been implemented, with the goal to tune model parameters to best agreement with reality.

LONGITUDINAL DYNAMICS

A simple first order model simulates the beam transport through the machine, considering the inhomogeneous dipoles and the correspondingly varying synchronous phases. Simulations predict a wide range of applicable settings concerning the rf-amplitudes and their associated phases. Calibration errors of the rf-amplitudes of ±5% cause deviations of the actual setup from the simulation, resulting in non-optimal settings of the corresponding phases. But to enable an easy and reliable operation of the HDSM the longitudinal parameters of the machine have to be set quite precisely. Due to the passage through two independent linacs only slight deviations of the parameters can induce drastically increased beam losses when the starting parameters were not chosen correctly. The visual difference of the measured phase advance between a correct setting and a bad one are too small to be recognized even by staff operators. Using the data of the different settings to optimise the model leads to poor results, as different rf-amplitudes will lead to similar fitting results, while the uncertainties of the measured phase data were still the restraining obstacle. Fig. 2 shows the determination of the first turn's phase which distinctly improved the situation by providing not only relative phase data but now absolute values [5]. Using this method after each new setup these newly gathered information can be used to apply the simulated starting phases for both linacs. Then only small variations of the phases cancel the remaining synchrotron oscillation, which makes it much easier to start and to operate the machine.

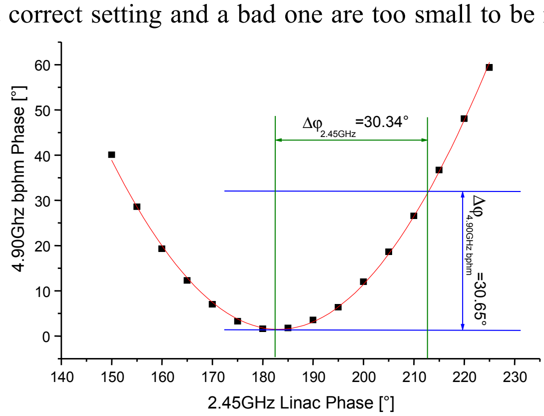

Figure 2: Determination of the first turn's phase of the 2.45 GHz linac using the longitudinal dispersion of the bending dipoles. The difference $\Delta\omega_{2.45Ghz}$ between linac phase for the extremum and the original arbitrary value of 212° is the first turn's phase ω_0.

Determining the Longitudinal Phase Space

To confirm the newly found settings, a tool was developed for an automated scanning and visualisation of the longitudinal phase space of the HDSM, using the high precision stepping-motor driven waveguide phase shifters. An example is illustrated in fig. 3. The large amount of phase-space data corresponding to one setting of the rf-amplitudes is used to optimise the model according to the measured data. The fitting algorithm uses only data were the beam reached full energy. At first the model is fitted individually to all the data. Afterwards the average value of the rf-amplitudes is used to fit the model globally to all data at once. But there are still discrepancies between the model and the machine which are now under investigation.

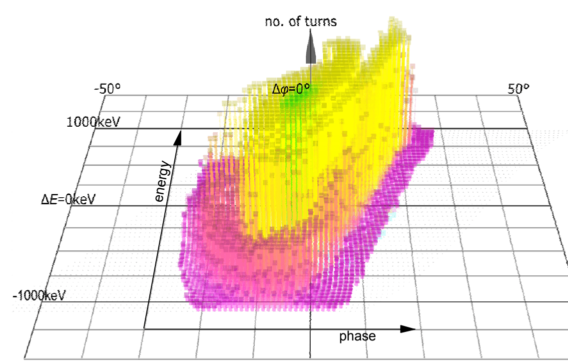

Figure 3: Measured longitudinal phase space acceptance of the HDSM. The number of achieved turns (max. 43) is given by the height of the bars. The green area in the centre marks relatively small synchrotron oscillations.

TRANSVERSAL BEAM OPTICS

Principle

In a linear model the beam optics in a microtron can be principally described by following matrix equation:

$$\Delta x = S \cdot \Delta w$$

where the vector Δw contains the changes of steerer kicks in all turns and Δx the resulting changes of all beam positions in both planes. S is a triangular-like matrix containing the beam optics of all turns, thereby describing the response of any change in the steerer settings. It depends on not precisely known parameters like dipole optics and

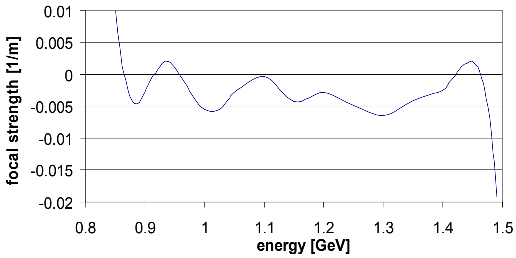

Figure 4: Dependence of vertical focal strength on beam energy in one of the dipoles calculated by ray-tracing.

quadrupole settings. To get a good agreement with theory, the dipole matrices were computed using a ray-tracing code with measured field maps as input. Fig. 4 shows the calculated vertical focal strength against the beam energy. Comparison with a full ray-tracing simulation of the HDSM approved an excellent agreement of this first order model; deviations turned out to be smaller than the accuracy of the bpms. However, it didn't reflect the properties of the actual beam optics; the actual transversal focusing is different. We assumed that this is mainly due to improper knowledge of the exact focal strengths of the quadrupoles, each of which is passed 43 times by the beam. To adapt *S*, which depends strongly non-linear on the focal strengths, the derivatives with respect to its parameter vector *p* were calculated analytically and then the model adapted to the measured data by minimizing the residuum r by application of singular value decomposition (SVD) :

$$\|r\| = \left\| \frac{\partial S\Delta w}{\partial p} \cdot \delta p - \left(\Delta x_m - S(p)\cdot \Delta w\right) \right\| = \min$$

Δx_{m} and $S\cdot\Delta w$ are the measured respectively the calculated beam position changes caused by an alteration of the steerers Δw. The result is a correction δp for the model-parameters, usually called shift-vector, which yields *p* for the next iteration step. Due to the strong nonlinearity in *p* a good initial value has to be found. To speed up the calculation, the whole parameter space was scanned and the data together with the counted number of betatron oscillations stored into a database. To find initial values, the program searches the database for parameter settings with nearly the same number of oscillations as measured and then starts to fit. The parameter settings found out by this procedure were able to sufficiently describe the response to a change of one steerer kick, but not, if other steerers were changed. Therefore the above minimization equation was expanded to fit a large set of steerer kick changes and beam responses simultaneously.

Results

The model fits showed, that the measured beam response cannot be explained only by a special setting of the quadrupoles. Two additional influences have to be assumed. Firstly, in the horizontal plane there is a defocusing effect in the upper turns and secondly, in the vertical plane the focussing is stronger than expected, independent of beam energy. The former can be explained by a slight magnetic field decay in the bending dipoles parallel to the pole face. The latter may result by a not ideal field gradient perpendicular to pole face. To adapt the model the curve in fig. 4 has to be adjusted upwards approximately by 0.007 m^{-1}. Using these modifications the measured beam response can be described fairly well. The result is shown in fig. 5 for the horizontal plane; the vertical plane fits as well. The right axis denotes the turn number in the HDSM, the upright axis the beam position variations caused by changing the kick of one steerer, whose position is noted on the left axis (there are 4 steerers in each turn). The free parameters for the fit are the 2 sensitivities (both directions) of each of the 4 bpms, the 8 quadrupole strengths and the described modifications in focal strength: an energy independent focusing in the vertical plane and a horizontally defocusing lens in the last 20 turns. Though these results are not yet confirmed by other measurements (a diploma thesis is in preparation [6]), the present simulation is sufficient to optimise the beam positions in the HDSM in the same manner as it is done in the RTMs.

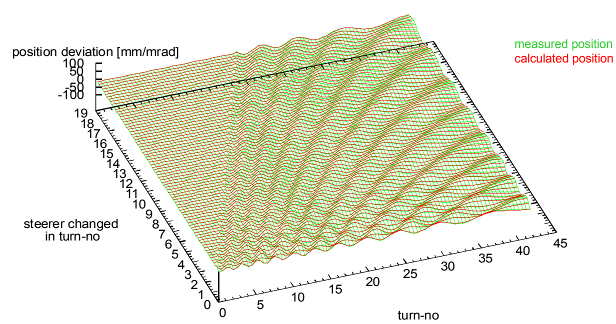

Figure 5: Responses of the first bpm on both linac axes when changing a steerer kick in turns 1-19. Only horizontal direction is shown. (Green: measured beam response. Red: model predicted response.).

OUTLOOK

Effective beam optimisation algorithms have been implemented for the HDSM based on models. The remaining work is to better understand discrepancies of the fitted model parameters to their settings in the real microtron and to speed up the fitting of the model, when beam optics of the accelerator has been changed.

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