AUTOMATED PHASE OPTIMIZATION FOR THE HDSM AT MAMI *

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Abstract

The Harmonic Double Sided Microtron (HDSM) at Mainz University is a very reliable stage of the 1.6 GeV CW microtron cascade MAMI [1, 2]. Nevertheless setting up and operating the machine depends largely upon an appropriate adjustment of the RF systems. To assist the MAMI operators, a new approach basing on the analysis of the synchrotron oscillation has been developed and enables the optimization of the RF phases of the linacs for the given RF amplitudes.

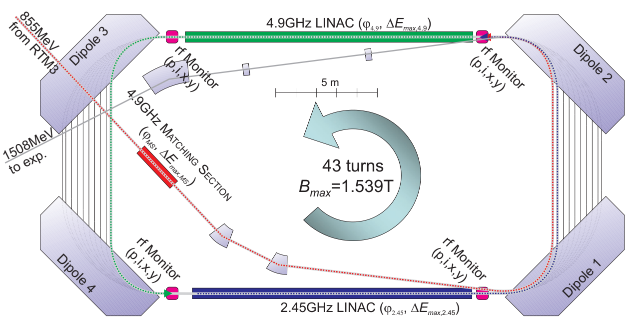

Figure 1: Plan of the HDSM.

LONGITUDINAL DYNAMICS

The longitudinal phase space of the HDSM is mainly influenced by the magnetic field of the bending magnet systems, the RF amplitude and phase of both linacs (Figure 1 illustrates the main components acting on the longitudinal dynamics) and the energy adjustment provided by the matching section. The magnetic fields and the RF amplitudes usually are set to their nominal values. To match the HDSM injection energy and phase the individual RF phases have to be optimized by the operator.

To accomplish this task, the injection energy is treated specially: During routine operation the RF phase of the matching section (ϕ_{MS}) is preset close to the zero crossing and the injection energy can easily be corrected by means of the phase:

$$\Delta E = \Delta E_{\mathrm{MS}} \cdot \sin(\phi_{\mathrm{MS}}) \sim 0.02\,\mathrm{MeV}/^\circ \qquad (1)$$

Energy adjustments may cause orbit distortions due to the transversal dispersion of the following injection beam line. Additionally, the longitudinal dispersion introduces a change of the injection phase which amounts to approximately 30°/MeV. Both effects had to be corrected manually by the operator.

Longitudinal Stability and Phase Advance

The longitudinal motion of the electron bunches in the HDSM can be expressed by matrix equations. If the coupling between longitudinal and transversal phase space is neglected, these matrices reduce to 2×2 matrices: one for each linac ($\mathcal{L}$) and one for each bending magnet system ($\mathcal{D}$). For one half turn, which corresponds to the elementary cell of the longitudinal motion of the HDSM, this yields [3]:

$$\begin{pmatrix} \delta\phi_1 \\ \delta E_1 \end{pmatrix} = \mathcal{L} \cdot \mathcal{D} \cdot \begin{pmatrix} \delta\phi_0 \\ \delta E_0 \end{pmatrix} \qquad (2)$$

where $\delta\phi_i$ is the phase deviation relative to the synchronous particle and δE_i the corresponding energy deviation before ($i = 0$) and after ($i = 1$) this part of the lattice. The longitudinal focussing power is determined by the maximum energy gain $\Delta E_{\max}$ and the phase ϕ of the bunch. Using the linear approximation of the sinusoidal RF wave, the matrices $\mathcal{L}$ and $\mathcal{D}$ for the linac and the bending system can be expressed the following way:

$$\begin{aligned} \mathcal{L} &= \begin{pmatrix} 1 & 0 \\ -\Delta E_{\max}\sin(\phi) & 1 \end{pmatrix} \\ \mathcal{D} &= \begin{pmatrix} 1 & -\frac{k \cdot 2\pi}{\Delta E_{\max}\cos(\phi)} \\ 0 & 1 \end{pmatrix} \end{aligned} \qquad (3)$$

As the acceleration process is "quasi"-periodic, Eq. 2 has to be evaluated for every half turn of the HDSM, starting with the first passage of the 4.9 GHz linac. For stable acceleration, the resulting product of the elementary cells has to be considered as a similarity transformation of the phase space with a matrix like Eq. 4, where Ψ denotes the phase advance of the rotation in the phase space and α, β and γ are the twiss parameters.

$$\mathcal{U} = \begin{pmatrix} \cos(\Psi) + \alpha\sin(\Psi) & \beta\sin(\Psi) \\ -\gamma\sin(\Psi) & \cos(\Psi) - \alpha\sin(\Psi) \end{pmatrix} \qquad (4)$$

The trace of $\mathcal{U}$ has to be equal or less than 2 to fulfll the stability criterion. For a symmetric DSM with two identical linacs this results in an interval of stable acceleration for $-51.8^\circ \leq \phi \leq 0^\circ$. The relation between the phase advance Ψ of the synchrotron oscillation and the beam phase ϕ is given by Eq. 5:

$$\begin{aligned} \mathrm{tr}(\mathcal{U}) &= (2 + \pi\tan(\phi_1)) \cdot (2 + \pi\tan(\phi_2)) - 2 \\ &= 2\cos(\Psi) \end{aligned} \qquad (5)$$

while for a HDSM the phase advance is written as:

$$\mathrm{tr}(\mathcal{U}) = (2 + \pi\tan(\phi_{4.9\,\mathrm{GHz}})) \cdot (2 + \frac{1}{2}\pi\tan(\phi_{2.45\,\mathrm{GHz}})) - 2 \qquad (6)$$

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SYNCHROTRON OSCILLATION

Given precise phase data, the phase advance of the synchrotron oscillation can be calculated with Eq. 6 for each turn. These phase advances then can be integrated and approximated by a Taylor polynomial to get a smoothed synchrotron oscillation phase for each turn t:

$$\Psi(t) = \psi_0 + \psi_1 \cdot t + \psi_2 \cdot t^2 + ... \qquad (7)$$

ψ_0 is the initial phase of the synchrotron oscillation and is affected by the injection phase and energy only. However, ψ_0 *cannot* be determined this way. The parameter ψ_1 denotes the phase advance per turn t if the synchronous accelerating phases were constant (as is the case in our RTMs). The HDSM with the dedicated field gradients to improve transversal focussing causes the migration of the synchronous phase. That results in a frequency modulation of the oscillation and thus introduces higher order terms in Eq. 7. The synchrotron oscillation itself is related to Eq. 7:

$$\begin{aligned} \delta\phi(t) &= A_0 \cdot \sin(\Psi(t)) \\ &= A_0 \cdot \sin(\psi_0 + \psi_1 \cdot t + \psi_2 \cdot t^2 + ...) \end{aligned} \qquad (8)$$

All information (i.e. the amplitude A_0 and the initial phase ψ_0) can only be obtained by directly fitting the synchrotron oscillation of Eq. 8 to the phase data [4]. This is a difficult task. The HDSM with its inhomogeneous bending magnets requires the precise isolation of the subjacent smoothed phase migration curve and the superimposed synchrotron oscillation (see top of Fig. 2). This subjacent phase migration however is a workaround - a smooth curve used for offset subtraction - and should not to be confused with a real applicable phase migration. This procedure has to be carried out for the measured phase data of both linacs individually.

This can be achieved simply by fitting a polynomial of sufficient order. But the curved shape of the phase migration has to be considered (minium $O(t^2)$) as well as the trend to deviate (at the boundaries) or even oscillate for higher order polynomials. A 4^{th} order polynomial gives sufficient accuracy [5]. Subtracting the latter polynomial from the measured phase data yields a reasonable oscillation if the amplitude of the oscillation is $\gtrsim 2°$. However, this global polynomial often fails to reproduce the subjacent phase migration for the two or three first turns and of the last turns if A_0 is too small.

OPTIMIZING THE INJECTION ENERGY AND PHASE

The analysis of the first turns is most interesting during routine operation: The operator has to adjust the injection energy and phase to minimize the amplitude A_0 of the synchrotron oscillation. All required information to optimize the longitudinal configuration is contained within the *initial* phase ψ_0 and amplitude A_0.

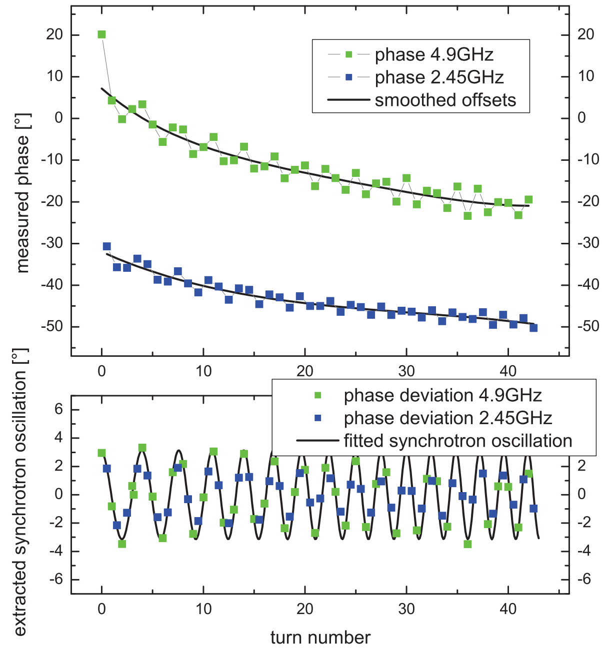

Figure 2: Typical phase measurement at 1.5 GeV with the smoothed offset data (top) and the analysis of the synchrotron oscillation (bottom). The synchrotron oscillation amplitude A_0 is approx. 3°, the initial phase ψ_0 is approx. $+100°$. According to Eq. 9 an energy correction of approx. +56 keV and an injection phase correction of $+1°$ would be neccessary to suppress the oscillation.

Optimization Strategy Relies on the Initial Phase of the Synchrotron Oscillation

The initial phase ψ_0 was examined in detail by means of the longitudinal acceptance measurements, which provides the phase measurement data in a systematic manner. This resulted empirically in simple rules (Eq. 9) on how to adjust the injection energy and phase to approach the configuration with least synchrotron oscillation amplitude ($\rightarrow$ center of Fig. 3). Briefly, the direction is determined by the initial phase ψ_0, and the amplitude A_0 determines the size of the iteration step. To reduce the number of iterations during an optimization, an additional offset of $-30°$ to ψ_0 was introduced to improve the direction of each step.

$$\begin{aligned} \Delta\phi &= A_0 \cos(\psi_0 - 30°) \\ \Delta E &= 0.02\,\mathrm{MeV}/° \cdot A_0 \sin(\psi_0 - 30°) \end{aligned} \qquad (9)$$

Also additional relative phase variations between both linacs could be used to accomplish the optimization. However, usually the relative phasing of both linacs varies significantly less than the injection phase relative to the preceding microtron cascade. Therefore and to keep the optimization routine as simple as possible the relative phasing is considered constant.

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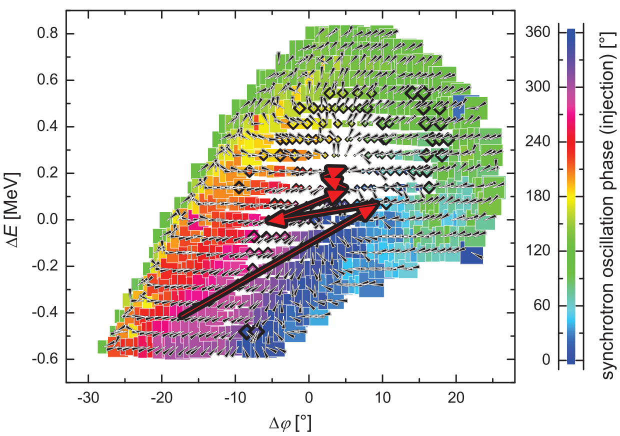

Figure 3: Longitudinal phase space acceptance measurement of the HDSM. The black arrows illustrate the direction of a step during the optimization according Eq. 9. The colors of the background represent the initial phase ψ_0 of the synchrotron oscillation. The amplitude A_0 of the oscillation is minimal in the center and growing towards the boundaries and therefore defines the size of the optimization step. The big arrows illustrate the steps for an optimization starting at an arbitrary point.

Performance of the Optimization Routine

First tests using the rules of Eq. 9 were very promising. The synchrotron oscillation is reliably reduced automatically, usually within less than five iterations, even if only 10 turns are reached right from the start.

But sometimes the algorithm fails to approach the best solution. Two possible reasons could be identified:

1. The phase ϕ_{MS} of the matching section is $180°$ out of phase. Phase variations to correct the injection energy cause energy variations in opposite direction then. Solution: The phase of the matching section has to be preset correctly.

2. The longitudinal phase advance approaches $180°$ (i.e. $Q = 1/2$) for the last turns causing instabilities and beam losses. Solution: An additional relative phase variation between both linacs has to be applied by the operator. This is, as mentioned earlier, not considered by the algorithm.

However, the oscillation could not be minimized lower than $2°$ reliably.

IMPROVEMENTS

Detection of Synchrotron Oscillations below $2°$

The offset treatment introduced above is sufficient for large synchrotron oscillation amplitudes. But for small amplitudes the separation between the smoothed phase migration and the synchrotron oscillation becomes even more important and polynomials are not adequate enough.

To exceed this limit, the analysis of the measured phase data was improved. The new strategy still uses the global polynomial fit for sychrotron oscillations larger than $2°$. For smaller amplitudes smoothing is achieved using a local regression method for each linac, similar to the strategy of kernel smoothers [6]. The problem at the boundaries (i.e. for the first three and the last three turns) is solved by extrapolating the smoothed data by means of a parabola.

The result of this algorithm is a smoothed phase migration which can now be subtracted from the measured data yielding the desired oscillation. This can be fitted by Eq. 8.

Furthermore, the fit of Eq. 8 also is more difficult with decreasing amplitude A_0. Due to the phase migration the phase advance of the synchrotron oscillation varies from approx. $90°$ at injection and approaches $180°$ at extraction energy, based on the current longitudinal configuration. Therefore the fitting parameters for Eq. 8 have to be initialized and constrained carefully to yield best results:

1. The amplitude A_0 is the easiest to confine; it is obtained by simply calculating the RMS amplitude of the remaining oscillation data (see bottom of Fig. 2).

2. The initial phase ψ_0 is preset by fitting only the first 5 turns.

3. The remaining arguments are initialized with the fit of Eq. 7, i.e. the progression of the longitudinal phase advance.

With this initialization the fit of Eq. 8 can now detect synchrotron oscillation amplitudes of less than $0.5°$ and the HDSM can be optimized accordingly.

CONCLUSION

This method proved to be a powerful and reliable tool for optimizing the HDSM, so it is now used routinely to assist the operators. In the future it may be possible to introduce the relative phase variation between both linacs automatically, if the longitudinal tune approaches the instable region.

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