# VARIOUS IMPROVEMENTS TO OPERATE THE 1.5 GeV HDSM AT MAMI *

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## *Abstract*

During the last three years at the 1.5 GeV Harmonic Double Sided Microtron (HDSM, [1]) of MAMI a lot of improvements concerning the longitudinal operation of the accelerator were tested and installed.

To monitor the rf-power dissipated in the accelerating sections, their cooling water flow and its temperature rise are now continuously logged.

Phase calibration measurements of the linacs and the phase/intensity monitors (p/i-monitors) revealed nonlinearities of the high precision step-motor driven waveguide phase shifters. They were recalibrated to deliver precise absolute values. Thereby it is now possible to measure not only the first turn's phase very exactly, but also to determine the linac's rf-amplitude within an error of less than 5 % using the well known longitudinal dispersion of the bending system. These results are compared to the thermal load measurements.

For parity violation experiments the beam energy has to be stabilised to some $10^{-6}$. A dedicated system measuring the time-of-flight through a bending magnet is now used in routine operation and controls the output energy via the linac phases.

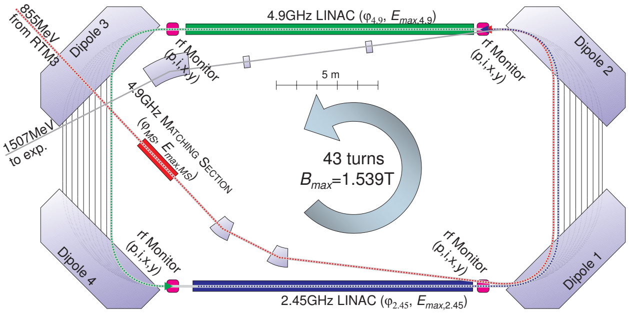

Figure 1: Plan of the HDSM.

## LONGITUDINAL DYNAMICS

In contrast to the homogeneous deflection magnets of an RTM the HDSM as presented in Fig. 1 has deflection magnets with a field gradient to compensate for the vertical fringe field defocusing. This causes the synchronous phase to slip down on the rf-wave turn by turn (see Fig. 2), which complicates the measurement of the phases and the rf-voltages. The settings of the two linacs are not unique but lead to many different possibilities which can be characterised by their different synchronous phase progressions for each turn and linac. In addition this progressing synchronous phase causes individual longitudinal tunes for each turn starting from $Q \approx 0.2$ at injection to $Q < 0.5$ at extraction energy. In 2009 the longitudinal dynamics of the HDSM was analysed more sophisticatedly. To improve the significance of the measured phase data and the resultant fitted model, independent systems to monitor longitudinal beam parameters were installed.

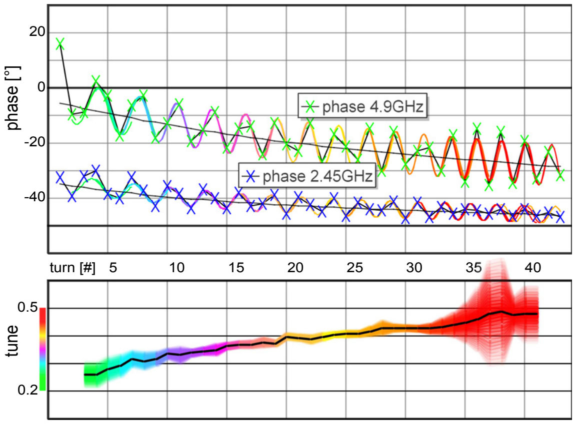

Figure 2: Typical phase progression with synchrotron oscillation of the HDSM's two linacs and the fitted longitudinal tunes with their uncertainties. Also different tune colours are used to illustrate Fig. 4.

## *Calibrated Phase Actuators*

At the beginning some effects concerning the reproducibility of the phase measurements were not understood. However, we discovered nonlinearities at our phase steering systems concerning the precision step-motor driven waveguide phase shifters: due to unavoidable reflections at their input/output coaxial circulator and coax-waveguide transition there are deviations of up to $\pm 10°$ from the ideal linear relation of phase change to waveguide-short position. Thus all those phase actuators were calibrated and are now operated with a precision better than $\pm 1°$.

This calibration led to improved reproducibility of the phase measurements, even after a longer shutdown period which occasionally requires major variations of the phase shifters while starting the HDSM.

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### *Monitoring the RF-Voltages*

The linacs rf-voltages were measured with precision powermeters via calibrated -50 dB waveguide-to-coaxial directional couplers. However, at the 4.9 GHz-linac the calibration curve changed over two years by up to 1.2 dB. The reason turned out to be a change of the insertion loss of 4.9 GHz stripline bandpass filters, which are to be inserted in every measurement path because of the strong harmonic 9.8 GHz output of the klystron TH2166. The reason for this change is still unknown. For higher redundancy therefore the cooling water flow at the rf-structures and its temperature rise are measured and logged continuously by calibrated water meters (±3 %) and a precise 3-wire Pt100-system (±0.1°C, i.e. 1.5 % at 6.5°C). Together with the known shunt impedances (±3 %) of the rf-sections this gives a good measurement of the accelerating voltages with elementary instruments.

Since the phase variations now can be done very precisely, the data to measure the injection phases [2] can also be used to measure the corresponding linac's rf-amplitude and phase. The fit uses the well known longitudinal dispersion of the following bending magnet system, but has to deal with the disadvantage of providing data for only a small part $< 10\,\%$ of the full sine-like dispersion curve due to the finite aperture. The upper diagram of Fig. 3 shows the injection phase of the 4.9 GHz linac when changing its rf-voltage, using the longitudinal dispersion of Dipole 3 and 4, compared to the measurement by the linac's p/i-monitor whose offset was determined with the dispersion method. The lower diagram shows the resulting rf-voltages using calorimetric data and the shunt impedances, compared to the fits using the longitudinal dispersion.

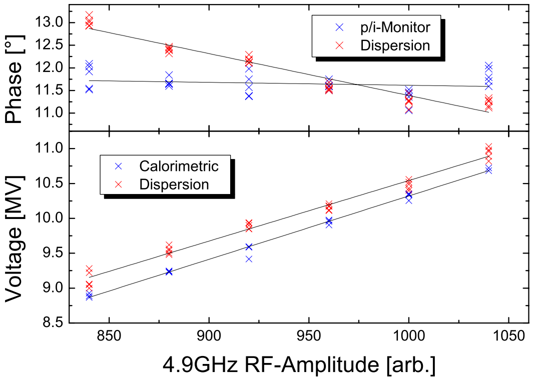

Figure 3: Comparison of different calibration measurements. The upper picture shows a slight change of linac phase caused by the rf-amplitude feedback system which is not detected using the linac's p/i-monitors. The lower picture shows the rf-voltages using calorimetric data resp. the longitudinal dispersion of Dipole 3 and 4.

## MEASUREMENT, FIT AND SIMULATIONS

### *Longitudinal Model of the HDSM*

The model to interpret the phase data of the HDSM uses the calculated return path lengths which result from the magnetic individual field maps of the HDSM dipoles and the particle tracking program PTRACE [3]. To represent the real machine at its best, the simulated beam's intensity decreases due to the finite aperture linearly when the energy deviates between 1-2 MeV and complete beam loss occurs above 2 MeV deviation compared to the reference energies. Coupling between longitudinal and transversal phase space may be considered in the future to improve the model even more.

### *Measurement and Analysis of the Longitudinal Phase Space*

It is possible to fit this model to a single shot of phase data, but the significance of the fitted parameters (i.e. the rf-voltages) is rather poor. To improve the situation many different phase settings within the current machine configuration can be applied and measured successively within a few ten minutes to provide as many data as possible. Recent measurements of the longitudinal phase space with the calibrated phase shifters now allow to distinctly change the injection phase without adding an unknown relative phase change between the linacs. At present it is possible to extract the longitudinal tune turn-by-turn by analysing five or more adjacent passages of one linac, while treating both linacs separately as illustrated in Fig. 2. For a particular setting of rf-amplitudes the shape of the tune curve does not change significantly, as long as the relative phase between both linacs persists. The measurements also show that areas approaching the forbidden resonant tune value of $Q = 0.5$ lead to a decreasing size of the accepted longitudinal phase space, as expected (cf. Fig 4).

### *Automated Fitting for the HDSM*

To automatically fit the model to the measured data with a Levenberg-Marquardt-algorithm it is necessary to mask out invalid data, which are measured faulty due to aperture limitations and lead to improper fit-steps. This is done by accepting only phase data, where all neighbouring measurements completed all 43 returns of the HDSM, which ensures that the model typically covers all individual measurements.

With all this, both the shape of measured and simulated acceptance and the longitudinal tunes show similar characteristics. One result for a standard rf-voltage setting is presented in Fig. 4. Many features of the measurement can be verified by the model. The rf-voltages resultant from the fit with 9.34 MV for the 4.9 GHz-linac and 8.95 MV for the 2.45 GHz-linac differ less than 5 % from the methods mentioned above with 9.7 MV and 9.1 MV.

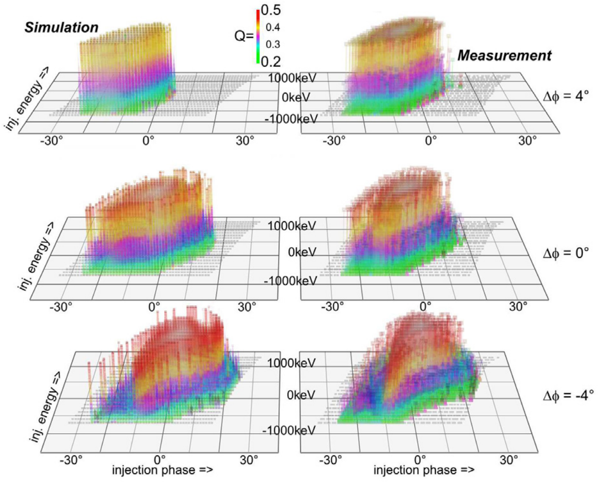

Figure 4: 3D-plot of measured and of fitted-model longitudinal phase space acceptance of the HDSM for different relative linac phases $\Delta\Phi$ related to 4.9 GHz. The height of each plotted bar shows the number of turns completed. Different colours represent the longitudinal tune reached (from green $Q = 0.2$ to red $Q = 0.5$, cf. Fig. 2).

The measurement routine itself was very helpful in finding a good working point for the HDSM when it was operated at 1.6 GeV for the first time [4] and it became a standard diagnostic tool.

## ENERGY STABILISATION

For parity violation experiments a very stable beam energy is required. An energy stabilisation system was developed for RTM 3 a few years ago stabilising the output energy to some $10^{-6}$ at 855 MeV [5, 6]. This installation measures the time of flight of the extracted beam in the last 180° bending arc with two 9.8 GHz $\text{TM}_{010}$ phase resonators and then varies the linac phase accordingly between 0 and 500 Hz. The HDSM's installation [7] is based on the same principle aside from measuring the time of flight in the last 90° arc with two 4.9 GHz resonators as sketched in Fig. 5.

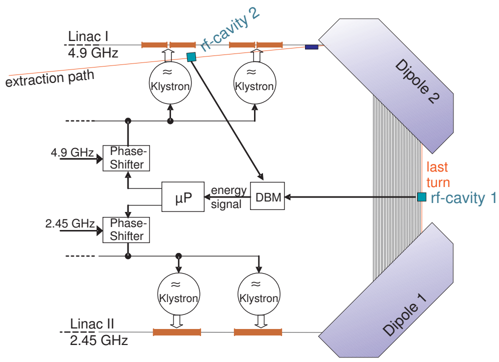

Figure 5: Layout of the main components of the HDSM's energy stabilisation system.

From simulations with PTRACE follows the relation between the measured phase $\Delta f$, the energy deviation $\Delta p$ and angle fluctuations $\Delta x'$:

$$\Delta f\,[^\circ] = -0.013^\circ \cdot \Delta p\,[\text{keV}] - 0.037^\circ \cdot \Delta x'\,[\mu\text{rad}]$$

Since angle fluctuations of some $\mu$rad produce phase signals of the same magnitude as energy fluctuations of a few 10 keV, also two position monitors were installed to be able to compensate for this effect in future. As yet the system for the RTM 3 showed only very small angle fluctuations well below the energy fluctuations. In both RTM 3 and HDSM the longitudinal dynamics must meet special requirements, such that the extracted beam energy can be controlled by varying the microtron's rf-phase. In case of RTM 3 this can be established by varying the synchrotron frequency by altering the rf-voltage, until the output energy shows maximum correlation to a change of the linac phase. For the HDSM there are two linacs to be controlled individually. To find a good working point an automated routine modulates the injection phase of the HDSM and measures the correlated output energy while heading for different relative phases of both linacs. As this method requires stable acceleration while changing the injection phase up to ±2°, also beam losses are considered to find a compromise between energy correlation and transmission.

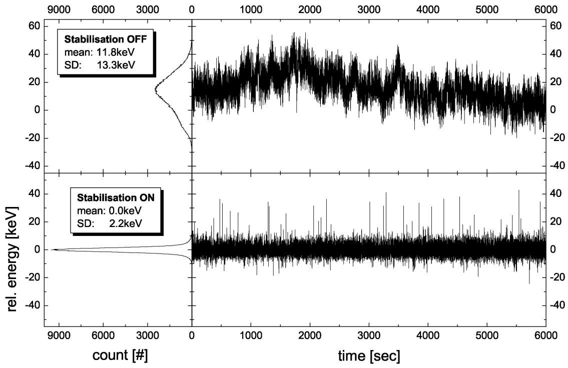

Figure 6: Effect of the energy stabilisation system of the HDSM. The data is averaged over 20 ms.

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