METHODS FOR HIGH-PRECISION BEAM ENERGY MONITORING AT THE MAINZ MICROTRON (MAMI) *

Th. Doerk, H. Euteneuer, K.-H. Kaiser,
Institut für Kernphysik, J.-Gutenberg Universität, D-55099 Mainz, Germany

Abstract

Methods for MAMI beam energy monitoring to 10^{-6} by rf-cavities are described. A system with two TM_{010}-resonators for time of flight through the 180°-dipoles is under construction. A setup with two TM_{110}-position monitors has already been installed. It measures the beam bending radii while compensating for energy-independent transverse influences. Results are reported.

1 INTRODUCTION

The experiments in nuclear and particle physics and the investigations for the generation of coherent x-rays at the 855 MeV racetrack microtron cascade MAMI [1] profit from the high energy stability and low emittance of its cw electron beam. Apart from an absolute energy calibration in 1992, no improvements were required since the beginning of the experiments five years ago. However, for a planned parity violation experiment the relative beam energy needs to be measured with a very high sensitivity. This is required as disturbing energy changes correlated with the direction of electron polarization are to be detected. In the following section the RTM characteristics are described briefly. Subsequently, various methods of high resolution energy measurements are discussed. Finally, the setup and first results of a recently installed system are presented.

2 THE BEAM ENERGY IN RTM3

For a correctly tuned injection energy and phase the mean energy in the 3rd racetrack microtron (RTM3) is given by

$$E = E_{\text{in}} + n \cdot \Delta E(1 + k \cdot n) =$$
$$\frac{e \cdot B \cdot c}{2\pi}\,[(m-1)\lambda - 2D + n \cdot \lambda(1 + k \cdot n)]. \quad (1)$$

(n: number of turn; E_{in}: 180.5 MeV: ΔE: 7.5 MeV per turn; k = 4.66$\cdot 10^{-6}$: correction factor for the deviation of the particle trajectory from the ideal racetrack shape (due to reversed field stripes) and for $\beta < 1$; $(eBc)/2\pi$ = 61.314 MeV/m for B = 1.28 Tesla; m: length of first revolution divided by the rf-wavelength λ (0.1224 m); D: effective distance between the magnets (12.85 m)).

The accuracy of E is determined by the homogeneity of the magnetic field B in the inner region of the 180°-magnets and by the precision of the effective distance between them. Thanks to field homogenizing surface coils, B is known absolutely to $1 \cdot 10^{-4}$. Its time stability is 10^{-6}, which is achieved by current regulation with respect to a NMR-probe. The effective magnet distance D depends on the accuracy of the fringe field measurements, the reproducibility of the field distribution, the magnet alignment quality and the floor temperature. Changes in these parametres could potentially add up to a maximum deviation of a few mm.

* Work supported by DFG (SFB 201)

3 MEASUREMENT OF THE ABSOLUTE BEAM ENERGY

The absolute beam energy was determined in 1992 [2] by measuring the distance between the common linac axis and the beam return paths n = 84, 86 and 88 of RTM3. This was achieved by precisely aligning a quadrupole magnet at the respective calculated return position. While it was switched on and off, the jump of the beam position downstreams was observed and subsequently minimized using a calibrated steering coil. After the corresponding bending radii were evaluated and all uncertainities taken into account, the energy was found to be within 200 keV in agreement with previous simulations.

This very satisfactory result was at least partly due to the fact that the field of the dipoles was always set up to 1.28 Tesla and shut down following a well-defined procedure. However, this procedure had to be partly abandoned during the last two years because the accelerator was sometimes run at higher end energies (up to 882 MeV for 90 turns instead of the nominal 855 MeV). Moreover, the field was up- and down-regulated by some 10^{-4} in order to obtain a desired spin orientation of polarized electrons at the target. Thus hysteresis and saturation effects may have affected the effective magnet distance D and consequently the beam energy calibration. This raised the need for a permanent energy monitoring system which is noninvasive and easily operable.

For this purpose an rf beam position monitor (BPM) was recently installed on the last turn (fig.1 and sect. 5). Given the beam stays correctly positioned on the accelerator axis, its mean signal voltage is proportional to the beam energy. The positioning can easily be achieved using a standard computer routine [3]. It measures the beam position by TM_{110}-cavities at both ends of the linac while the beam intensity is modulated by 10 nsec-diagnostic pulses to distinguish the different turns. The beam direction is corrected by a matrix algorithm using weak dipoles on the return

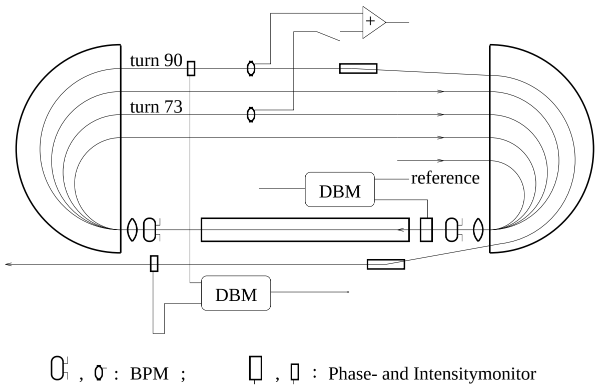

Figure 1: Scheme of the arrangements for the energy measurement

paths. In cw operation, however, the position on the accelator axis can only be controlled indirectly by measuring the beam position and direction in the injection line to 10 μm and 1 μrad, respectively. The beam position on the RTM3 axis should be controlled regularly. This raises the need to interrupt sensitive experiments every few hours for a few minutes. So the beam energy can be measured absolutely with an accuracy of ±200 keV. The reproducibility is ±20 keV.

4 MEASUREMENT OF ENERGY FLUCTUATIONS

The energy spread of the beam at 855 MeV is too small to be measured directly in the existing setup. This is due to the strong phase focusing of the RTM and the good longitudinal matching between the three stages. The width of the intrinsic distribution is given by the injected longitudinal phase space volume and the stochastical energy loss by synchrotron radiation in RTM3. Both effects add up to about 25 keV FWHM. In addition, however, there are msec-fluctuations and also long-term drifts of the beam energy. These are due to small phase and amplitude variations of the accelerating rf, which lead to a higher effective energy spread. Furthermore, they may be correlated to other parameters, e.g. the beam current for different electron polarizations. In the following sections, two methods for the detection of energy fluctuations and drifts are discussed.

4.1 Bunch phase detection

Using diagnostic pulses the bunch phase for each turn can be measured at a few tenths of a degree by means of a TM_{010} rf-cavity on the accelerator axis respective to a common reference. The analysis of these phase oscillations as a function of the recirculation number was used at the beginning of MAMI to tune the microtrons to the designed synchronous phases. Also, it served to verify the correct functioning of the microtron cascade with regard to its designed longitudinal characteristics. Synchrotron phase advances and eigenellipse parameters are well known from these investigations. Therefore, beam energy deviations can be easily deduced in each turn from phase changes. However, the intense diagnostic pulses have to be turned off for most of the experiments. This creates a need for a new method which would be applicable to the cw beam.

A simple system could be used to measure fluctuations of the bunch energy consisting of one TM_{010}-cavity in front and one behind the last 180°-deflection and a DBM detecting the phase difference between cavity signals (fig. 1). It uses the fact that the time of flight through the 180°-dipole is directly proportional to the electron energy. The resolution approximates 10 keV/° in RTM3 at the 3rd harmonic of the operating frequency (sect. 5). This measurement is slightly distorted by the dependence of the time of flight on the horizontal beam entrance angle. In the higher return paths the angle fluctuations are in the order of ± 2 μrad leading to a phase variation of $\pm 0.01^\circ$ only. The installation of this system is scheduled for July 1996.

4.2 Detection of beam positions

A high resolution energy measurement using a simple position detection on the return lines would be disturbed by the influence of transverse beam fluctuations (e.g. caused by small ac magnetic fields). Therefore, a special method based on two TM_{110}-BPM's is used in MAMI. This method makes use of the fact that the betatron frequency is decreasing with turn number, whereas the synchrotron oscillation wavelength remains constant. A setting can easily be found by fine tuning of the horizontal and longitudinal focussing, where there are 1.5 horizontal oscillations and 4 synchrotron periods between turns 73 and 90. Pseudo-damping and decreasing focussing power of the quadrupole doublets at both ends of the linac result in a constant betatron amplitude in this energy region. The sensitivity of the arrangement for energy deviations is doubled by adding the equally calibrated signals of both BPM's. On the other hand, horizontal beam vibrations are canceled as long as they are not produced behind turn 73 or on the common linac axis. Since the intensity ripple of the MAMI-beam is in the order of 1%, the signal has to be normalized with repect to the mean current only.

5 THE CAVITIES

Due to the small distance of λ/π between successive return paths the TM_{110}-cavities were designed for 9.8 Ghz which is the 3rd harmonic of the operating frequency (fig. 2). For a given Q-value, coupling and frequency tuning, the power of this mode excited by the traversing electron bunches depends quadratically on both their displacement and intensity. This results in a respective linear dependence for the detected voltage. The linearity of the whole setup has been tested with the electron beam. The horizontal orientation of the TM_{110}-mode inside the pillbox cavity is forced by two small cylinders which detune the unwanted vertical mode by -280 MHz. The output coupling is done purely electrically in order to reduce small influences of the TM_{010}-mode (at 6.3 GHz), which is only sensitive to the beam intensity. This guarantees that the phase difference between the TM_{110}- and the distant TM_{010}-mode is close to 90°. Therefore, the latter is suppressed by the DBM. Further reduction was achieved by using two symmetrical pin-antennas and combining their output signals through a 180°-hybrid. No TM_{010}-signal could be observed with the new cavities, even when detuning the reference phase by 90°. This was in contrast to our experience with loop-coupled 2.45 GHz-cavities built earlier for the beam transport systems between and behind the RTMs. At the location of the last cavity, the 1σ-horizontal beam size is about 0.7 mm. Intensity losses due to the 8 mm cavity aperture, estimated from earlier halo measurements [4], should be of the order of 10^{-7} only.

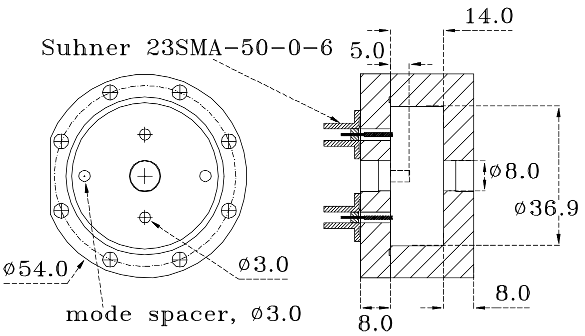

Figure 2: Scaled scheme of the TM_{010}-cavities (operational frequency: 9.86 GHz, Q_0 = 7500, coupling constant κ = 2, measures in mm).

6 MEASUREMENTS

After installation of the two cavities the beam position was measured in the return paths 73 and 90. Also the respective beam angles were determined to verify the absolute energy. This was done indirectly, from the excitation of the correcting coils in return path 73 and with a quadrupole as a second position monitor in turn 90. The result lay within 0.1 MeV of the value obtained earlier [2]. The beam position was measured with a time constant larger than 20 msec for more than 1 hour without any modification of MAMI. Thus information was gained about the stability of the mean energy (fig. 3b). The short-time stability was below 10 keV. However, there were temporal excursions of up to 50 keV. These were probably generated by phase changes produced by the automatically driven tuning plungers in the accelerator sections.

An extract of the short-time behaviour of the beam position is depicted in fig. 3a. There is a dominant 50 Hz oscillation with an amplitude of about 0.1 mm on both position monitors. This nearly disappears when both signals are added (and divided by 2) for the suppression of the transverse beam motion. The resulting energy signal contains mainly a 300 Hz component. This can easily be explained by the klystron power supplies ripple getting through the rf-amplitude control loop. A near-Gaussian distribution with a standard deviation of only 1.8 keV, i.e. $2.1 \cdot 10^{-6}$ is obtained by assorting all energy values taken every msec during a 10 sec run (fig. 3d, histogram a). Measured with a larger time constant (fig. 3c), the beam energy in this suppression mode showes the same typical structure as the one shown in fig 3b. As a consequence of the 300 Hz suppression by integration, the resolution of the energy curve is better than 1 keV.

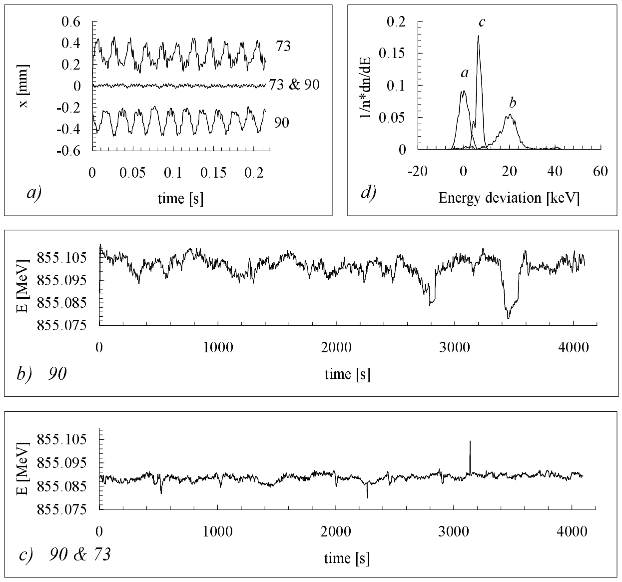

Figure 3: Measurements using the TM_{110}-cavities:
a) Beam position x as a function of time (extract of a 10 sec run) in the return paths 73 and 90 and sum of both signals (the curves were not recorded simultaneously).
b) and c) Longtime behaviour of the beam energy E from cavity 90 and from cavities 73 & 90, respectively.
d) Histograms of the energy values recorded during the measurements a) to c).

7 REFERENCES

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