# AUTOMATIC BEAM-STEERING OF THE MAINZ MICROTRON

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## Indroduction.

The Mainz Microtron (MAMI) will consist of three cascaded Race-Track-Microtrons with a Van De Graaff as injector.[1] The first stage, delivering an output energy of 14 MeV, has been working for about two years in the Institut für Kernphysik in Mainz. The second stage is presently under construction and will increase the output-energy to 180 MeV.

A principal problem with these microtrons is the precise positioning of each individual turn to the middle-axis of the accelerating rf.-section. Therefore in front of and behind the section monitors for detecting the beam-position in each of the 20 turns of the first stage has been installed. A computer reads out this data and determines the setting of the 80 steering coils in the return-tracks of the beam (two coils in horizontal and vertical direction for each turn). The following describes the details of the hard- and software of this system shown in fig.1.

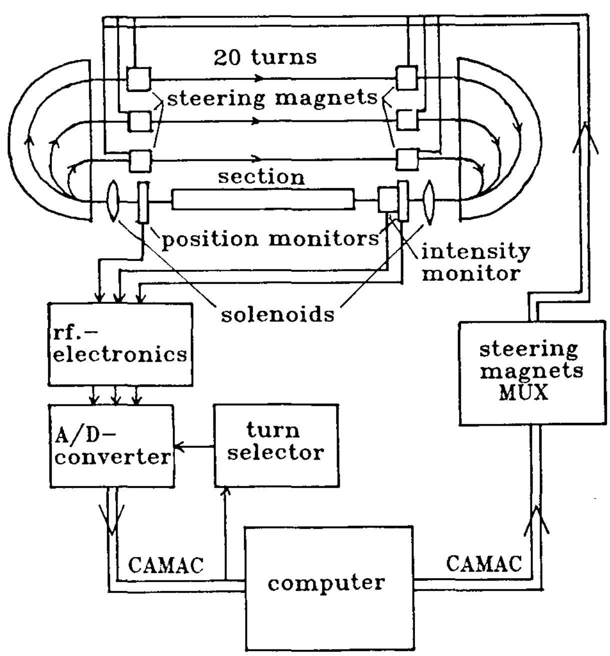


Fig.1 Scheme of the hardware for the automatic beam-steering system.

## The Position-Monitors and Steering Magnets.

The beam-monitors consist of square rf.-cavities, in which the electron -beam excites a rf.-wave of the accelerator-frequency (TM210-mode). Two antennas are positioned in such a manner, that a beam deviation off the middle-axis in x- and y-direction produces independent signals. To get the signals from each revolution the beam is marked with short pulses of about 8 kHz repetition rate. When such a pulse runs through the microtron it passes the monitors in each turn and produces a signal change, which depends on the beam-deviation. After some rf.-electronics and differentiation,[2] we get the signals on the oscilloscope (Fig.2). Every peak on the photographs corresponds to one turn, its amplitude is proportional to the beam-intensity and in the position signals also to the deviation in the turn.

These signals are fed into a fast 12 -fold CAMAC-ADC, where the contributions of the individual turns are cut out by appropriate gate-signals, generated by a programmable delay-generator. Special electronics provides for the repeative starting of the ADC for all turns,[3] so that the computer can average the digitalized data thus reducing noise contributions. After calculating the new settings of the steering coils in a complex algorithm the computer delivers this data via CAMAC to a multiplexed digital/analog-converter with sample and hold circuits, which supplies the steering magnets.[4]

## The Mathematical Description of the Transversal Microtron-Optics.

In the optimisation algorithm the microtron is described in a first order matrix-formalism for particle beam-optics. The beam is represented by a vector (x,x',y,y'), where x,y are the deviations from the nominal position, x',y' are the corresponding angular-deviations. Due to the special optics there is no coupling between horizontal and vertical beam position. Therefore the problem is reduced to only one direction (x,x'). So the i-th turn of the microtron can be described by the equation:

$$x_i = A_i x_{i-1} + S_i(u_i - \overline{u}_i),$$

where $x_i$ is a vector, which contains the beam-deviations measured by the two monitors. $u_i$ is the actual setting of the two steering magnets and $\overline{u}_i$ is the optimal setting, which is not necessarily zero, because of errors in real optics. $A_i$ is a matrix standing for the condensed optics of one turn, $S_i$ describes the optical behaviour from the steering magnets to the following monitors. To describe all turns i=1,...,20 of the microtron, the above equation is recursively inserted in itself getting a system of equations:

$$\begin{pmatrix} x_1 \\ \cdot \\ \cdot \\ \cdot \\ x_n \end{pmatrix} = \begin{pmatrix} S_1 & & \emptyset & \\ A_2S_1 & S_2 & & \\ A_3A_2S_1 & A_3S_2 & S_3 & \\ \vdots & \vdots & & \ddots \\ A_n\cdots A_2S_1 & A_n\cdots A_3S_2 & \cdots & S_n \end{pmatrix} \left( \begin{pmatrix} u_1 \\ \cdot \\ \cdot \\ \cdot \\ u_n \end{pmatrix} - \begin{pmatrix} \bar{u}_1 \\ \cdot \\ \cdot \\ \cdot \\ \bar{u}_n \end{pmatrix} \right)$$

(n=20 is the number of turns)
or in short form:

$$x = C ( u - \bar{u} )$$

The following algorithms are based on the above equation.

## One-Step-Algorithm.

One could think of an algorithm for steering as follows:[5]

$$\Delta u = - C^{-1} x ,$$

where a correction $\Delta u$ for the steering magnets would be calculated from the measured beam-deviations x. Theoretically this algorithm should converge if repeated often enough, but in practice noise caused by many sources prevent the algorithm from converging. Averaging of the data improves this only to some extent but takes too much time.

## Least-Square-Fit Method.

An improved algorithm , which takes the noise much better into account, interprets the problem as a minimization-task of a statistical function. We choose a function, which describes the difference between the measured deviations x and the corresponding theoretical values $x^{(th)}$, calculated with a parametrized model of the microtron (analogous to a $\chi^2$-minimization).

$$\mathcal{L} = ( x - x^{(th)} )^T ( x - x^{(th)} ) .$$

This function is minimized by setting the derivative to zero. This leads to the one-step algorithm described before. In order to take more than one step into account a number of measurements is added:

$$\mathcal{L}^k = \sum_{j=1}^{k} ( x^j - x^{(th)j} )^T ( x^j - x^{(th)j} )$$

The index j indicates the number of the measurement. Minimizing in standard way with the optimal settings for the steering magnets $\bar{u}$ as minimization parameters leads to

$$\bar{u}^k = \frac{1}{k} C^{-1} \sum_{j=1}^{k} (Cu^j - x^j)$$

In order to cancel out the deviations between model and reality the steering magnets are set to the computed value for $\bar{u}$ after each measurement. So we get:

$$u^{k+1} = \frac{1}{k} C^{-1} \sum_{j=1}^{k} (Cu^j - x^j)$$

k now indicates the iteration step. This iteration, where all data have the same weight, could already be used to optimise the beam-position, but it is desirable to supply new data with more weight than the older one. The simplest way to do this is the multiplication of the sum-elements with a power-series. The factor is $(1-\varepsilon)$, where $\varepsilon$ is a small number between 0 and 1. $\varepsilon$ gives the rate of "forgetfulness" of the algorithm. So we find:

$$u^{k+1} = C^{-1} \left[ \frac{\varepsilon}{1-(1-\varepsilon)^k} \sum_{j=1}^{k} (1-\varepsilon)^{k-j} \cdot (Cu^j - x^j) \right]$$

The fraction at the left hand side of the sum is for normalization-purposes.
Programming the algorithm is very easy and doesn't need much computer-memory due to the simple form of the matrix C.

## Practical Experiences.

Fig.2 shows photographs of the analog position- and intensity-signals of the monitors before and after optimisation.

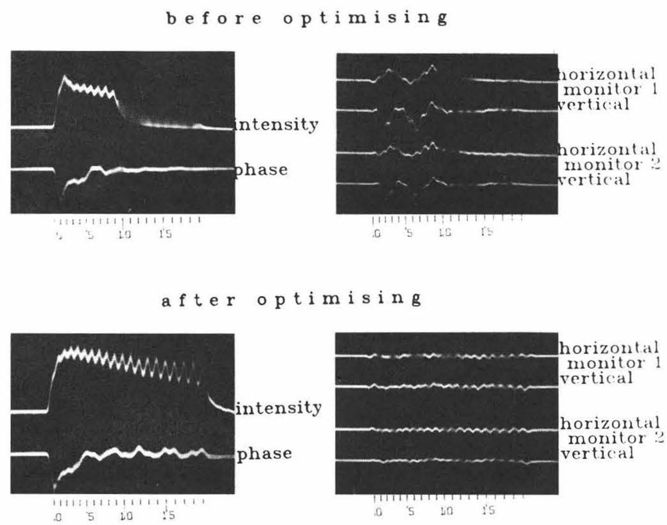


Fig.2 Intensity- and position-monitor analog-signals before and after optimising.

Before optimisation the beam makes only a few turns and then disappears in the wall of the beam-pipe. After optimisation the beam gets through the whole microtron and the position signals are very small. This means the beam is close to its optimal position. The optimisation-program has been successfully used for about 1 year in microtron operation of the first stage. At present the beam-position-optimisation takes about one minute, but an optimized version of the program could reduce this time to a few seconds.

## Optimisation of Other Parameters.

The speed of the optimisation-process depends on how accurately the system can be described by the mathematical model. There are certain parameters, which are not known well enough. For example in our microtron we didn't know the scaling of the position monitors (what deviation gives which signal) and due to technical reasons we didn't know the exact focal length of the solenoids.
So it was desirable to find a way to get these parameters by looking at the transversal behaviour

of the beam.
For the solution of this problem the same procedure is used as before. The differentiated function $\mathfrak{F}$ must be solved for the parameter-vector p we try to optimise. This only is possible with a linear dependence of the theoretical deviations on the parameters. As the focal length of the solenoids appears in the 40th power in our microtron-description it is necessary to make a first order Taylor-expansion of x and find the correct result by iteration of the expanded equation. For one step we get:

$$\left(\frac{\partial x}{\partial p}\right)^T \left(\frac{\partial x}{\partial p}\right) \delta p = \left(\frac{\partial x}{\partial p}\right)^T (x - x^{(th)})$$

where $\frac{\partial x}{\partial p}$ is the derivative of the theoretical data $x^{(th)}$, and x is the measured data. $\delta p$ now gives a correction of the parameter-vector p, which improves the model for calculating $x^{(th)}$. For our problem we write the monitor scaling values and the focal length into the parameter-vector. Then we make two measurements with different steering-magnet-settings with the difference $\Delta u$. In this case the microtron-behaviour can be described by:

$$\Delta x^{(th)} = C\,\Delta u$$

Now the function $\mathfrak{F}$ is minimized by repeated improvement of the model C with

$$\delta p = \left[\left(\frac{\partial C}{\partial p}\Delta u\right)^T \left(\frac{\partial C}{\partial p}\Delta u\right)\right]^{-1} \left(\frac{\partial C}{\partial p}\Delta u\right)^T (x - C\Delta u)$$

until $\delta p$ becomes small. Fig.3 shows a picture of a measured and a computed signal $\Delta x$ after parameter-optimisation.

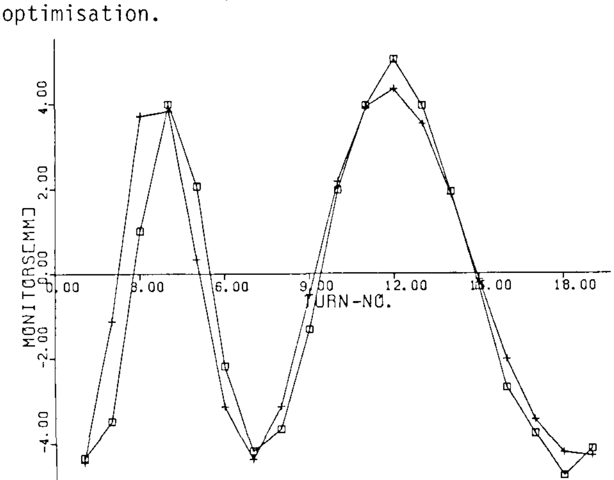


Fig.3 Comparison between measured (◻) and calculated (+) beam-position change after changing a steering magnet in the first turn.

Although it would be desirable to determine the optimal steering-magnet settings and the other parameters in one procedure. It is not practical because this algorithm needs more computing time and due to strong intercoupling of parameters it takes much more time for it to converge. So we have chosen to keep both procedures separate and use the data of the one procedure as input for the other. Once determined, monitor-scaling and focal length are stable enough to be used as input for the beam-position-optimisation procedure for some time.


1 H. Herminghaus, A. Feder, K.H. Kaiser, W. Manz, H. v.d.Schmitt, "The Design of a Cascaded 800 MeV Normal Conducting C.W. Race Track Microtron," Nuclear Instruments and Methods 138(1976)1.

2 B. Mertin, "Das Hochfrequenz-Strahlmonitorsystem für die 14 MeV-Stufe des MAMI-Projektes," Internal Report KPH 5/80 Institut für Kernphysik/Mainz (1980).

3 W. Heyne, "Rechnergestützte Erfassung schneller Strahlmonitorsignale und die Steuerung von Teilgeräten des MAMI-Projektes," Internal Report KPH 20/81 Institut für Kernphysik/Mainz (1981).

4 H.-J. Kreidel, "Das System zur selbsttätigen Optimierung der Strahllage im Mainzer Mikrotron," Internal Report KPH 16/81 Institut für Kernphysik/Mainz (1981).

5 W. Vollmer, "Regelungsprobleme am Mainzer Mikrotron," Diplomarbeit, Mathematics/Universität Mainz (1980).


Discussion

We haven't had a problem with the $TM_{111}$ mode because our structure doesn't support it.

If we were to build a whole array of these, we would feed them upside down, similar to a Cornell proposal.

We have started some studies on system stability to alignment errors and drifts. The only thing that looks serious is to create nondispersive beams in the linacs. The transverse optics appears to be quite insensitive, but the longitudinal is a serious problem. The beam dispersion has very low tolerances and requires a very sophisticated diagnostic system.

We have allowed for a factor of about 400 in emittance growth for synchrotron radiation loss.

We can steer the beam to within 0.5 mm of the linac center line; this is limited by the 6-bit accuracy of the steering coil readout and could be done better in principle.

We have only one bunch belonging to a given turn in the linac section at the same time. We find that the digital calculations compare well with the beam simulation method.

We calculate the extracted plasma sheath profile by assuming it follows the spherical curvature of the electrode; this is another case where the beam-simulation codes give you a check. We haven't done any calculations or experiments on the shape of the extraction electrodes inside the plasma chamber.