THE AUTOMATIC CONTROL OF THE EINDHOVEN AVF-CYCLOTRON

G.C.L. van Heusden, J. Halders, P. Kooy and R. Reumers

Eindhoven University of Technology, Eindhoven, Netherlands

F. Schutte

Free University, Amsterdam, Netherlands

Abstract

At the Vancouver Conference in 1972 the plans regarding the non-intercepting automatic control of the Eindhoven AVF-Cyclotron were presented.
In this paper we will show experimental results regarding the performance of the operating control system. A description of the control schemes used is given. The system consists of three main parts: 1) the HF-phase control loop, 2) the extraction efficiency optimization and 3) the control of the elements in the beam guiding system. The systems 1) and 2) are treated here in detail.

1. Introduction

For a closed loop computer controlled operation of the Eindhoven AVF-Cyclotron a system was built which uses instantaneously measured beam properties as input data[1]. At the Vancouver Conference in 1972 the first results concerning our non-intercepting beam diagnostic equipment were presented[2].
General control schemes, used in the various control loops, are given in section 2. Further, in section 3, the results of two control loops are given in detail:

1) The HF-phases of the particles at five radii are controlled by three concentric correction coils (section 3.1),
2) The optimization of the extraction efficiency is carried out by use of four harmonic trim coils (section 3.2).

The control loops of the horizontal and vertical position of the beam in the beam guiding system and the intermittent control of the magnetic induction of two 45° bending magnets in the energy analysing system are mentioned briefly in section 3.3.
A single crate CAMAC system is used for the data acquisition. Corrections on the parameter settings are performed by stepmotor driven ten-turns potentiometers, controlled by the CAMAC system.
The computer used is a DEC PDP-9 with 24 K core memory. The real time operating system basically consists of three parallel task-queues with different (software) priority levels and a serial task-queue for each control loop. Tasks for on-line experiments can also be handled during computer controlled operation of the cyclotron.

2. General control schemes

In this section the control schemes used are given. To find criteria for the decision which and how many parameters are needed in a particular control loop, the problem is formulated slightly different from the treatment given in ref. 1 and 2.
The beam properties to be controlled are represented by the vector $\underline{r}$ and the control parameters by the vector $\underline{p}$. The beam properties can be devided into two categories: 1) the properties which have prescribed values (e.g. the HF-phase) and 2) the properties which have to be optimized (e.g. the extraction efficiency):

1) For small variations the relation between $\underline{r}$ and $\underline{p}$ is considered linear and is given by a variation matrix A:

$$\underline{r} = A\,\underline{p} \quad \text{with } a_{ij} = \partial r_i/\partial p_j \tag{1}$$

2) For properties which have to be optimized, a quadratic relation is assumed between a single beam property r^* and the parameters $\underline{p}$:

$$r^* = a^*_{ij}\, p_j\, p_i \tag{2}$$

A 'new' beam property r_i can be defined as:

$$r_i = \partial r^*/\partial p_i \tag{3}$$

which has in the optimum of r^* the 'prescribed' value zero. The relation between the 'new' beam properties and the parameters is linear and is again given by a variation matrix A:

$$\underline{r} = A\,\underline{p} \quad \text{with } a_{ij} = \partial r_i/\partial p_j = \partial^2 r^*/\partial p_i \partial p_j \tag{4}$$

In this manner the beam properties of the second category are treated in the same way as those of the first category.

The beam properties $\underline{r}$ form an N-dimensional space R_N. The number of beam properties don't need to be equal to the number of control parameters. In general the parameters $\underline{p}$ form an M-dimensional subspace P_M of R_N. Corrections on the beam properties $\Delta\underline{r}$ can be performed only in the subspace P_M.
The corrections on the control parameters $\Delta\underline{p}$ can be determined from the projection of $\Delta\underline{r}$ on the subspace P_M. The distance between $\Delta\underline{r}$ and P_M represents the remaining error which cannot be corrected.
First the following definitions have to be given:

1) an orthonormal base of R_N: $\underline{\varepsilon}_i$
with $i = 1,2,\ldots,N$
$$(\underline{\varepsilon}_i \cdot \underline{\varepsilon}_j) = \delta_{ij} \tag{5}$$

2) the 'parameter' base of P_M: $\underline{\pi}_j$
with $j = 1,2,\ldots,M$
$$\underline{\pi}_j = p_{ji}\, \underline{\varepsilon}_i \tag{6}$$

3) an orthonormal base of P_M: $\underline{\mu}_k$
with $k = 1,2,\ldots,M$
$$(\underline{\mu}_k \cdot \underline{\mu}_l) = \delta_{kl}, \quad \underline{\mu}_k = s_{kj}\, \underline{\pi}_j \tag{7}$$

The projection of $\Delta\underline{r} = \Delta r_i\, \underline{\varepsilon}_i$ on the orthonormal base $\underline{\mu}_k$ of the subspace P_M is given by the scalar product:

$$\alpha_k = (\underline{\mu}_k \cdot \Delta\underline{r}) = s_{kj}\, \underline{\pi}_j \cdot \Delta r_i\, \underline{\varepsilon}_i = s_{kj}\, p_{ji}\, \Delta r_i \tag{8}$$

However, to know the corrections $\Delta\underline{p}$ of the control parameters, the projection of $\Delta\underline{r}$ has to be expressed on the parameter base $\underline{\pi}_j$.

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 553-556

The correction vector $\Delta \underline{p}$ can be expressed in both $\underline{\pi}_j$ and $\underline{\mu}_k$:

$$\Delta p_l^T \, \underline{\pi}_l = \alpha_k^T \, \underline{\mu}_k \qquad (9)$$

From this equation it follows that the corrections Δp_l can be determined from:

$$\Delta p_l = s_{lk}^T \, s_{kj} \, p_{ji} \, \Delta r_i \qquad (10)$$

or in matrix notation:

$$\Delta \underline{p} = S^T \, S \, P \, \Delta \underline{r} \qquad (11)$$

From the fact that the base $\underline{\mu}_k$ is orthonormal, i.e. $(\underline{\mu}_k \cdot \underline{\mu}_l) = \delta_{kl}$, it follows that:

$$s_{lk}^T \, s_{kj} = (p_{lk} \, p_{kj}^T)^{-1} \qquad (12)$$

Therefore the corrections can be calculated also from the equation:

$$\Delta \underline{p} = (P \, P^T)^{-1} \, P \, \Delta \underline{r} \qquad (13)$$

Equation (13) is the same result as obtained with the least squares method described in ref. 1 and 2. (Note that $P = A^T$).
The orthonormal base $\underline{\mu}_k$ of the subspace P_M, or even the base of R_N, may be choosen freely, e.g. the normalized ortogonal Chebishev polynomials[5]. These polynomials are graphically shown in fig. 2.1 for N=5.
If m_{kj} is the j^{th} element of $\underline{\mu}_k$, an auto correlation coefficient c_k of each base vector $\underline{\mu}_k$ can be determined from:

$$c_k = \frac{m_{kj} \, m_{(j+1)k}^T}{\frac{1}{2}m_{k1}^2 + m_{kj} \, m_{jk}^T + \frac{1}{2}m_{kN}^2} \qquad (14)$$

The coefficients c_k are also given in fig. 2.1. Note that the number of 'zero crossings' increase and the auto correlation coefficients c_k decrease with increasing k. Measured deviations $\Delta \underline{r}$ pointing in the direction of base vectors $\underline{\mu}_k$ with negative coefficients c_k cannot be distinguished from noise. Therefore only parameters $\underline{\pi}_j$ in the direction of base vectors with positive c_k are usefull. In the case of N=5, only the first three Chebishev polynomials (F1..F3) have positive c_k and consequently only three parameters are needed (M=3). If there is still meaningfull information in the other two directions, more measuring points are needed.

3. Results

3.1 The HF-phase control loop

A simplified block schema of the HF-measuring system is given in fig. 2.1 of ref. 4. The HF-phases are measured at five radii (30(5)50 cm).
Conform the remarks mentioned in section 2, the concentric correction coils B4, B6 and B10 (at radii 26, 38 and 60 cm) are choosen to control the phases. The measured variation matrix for 20 MeV protons is given in table I. The normalized actions of these parameters are shown in fig. 2.1. From this figure one may observe that B4 corresponds with F1, that B10 will have an important projection on F2 and B6 on F3. The projections of the parameter actions

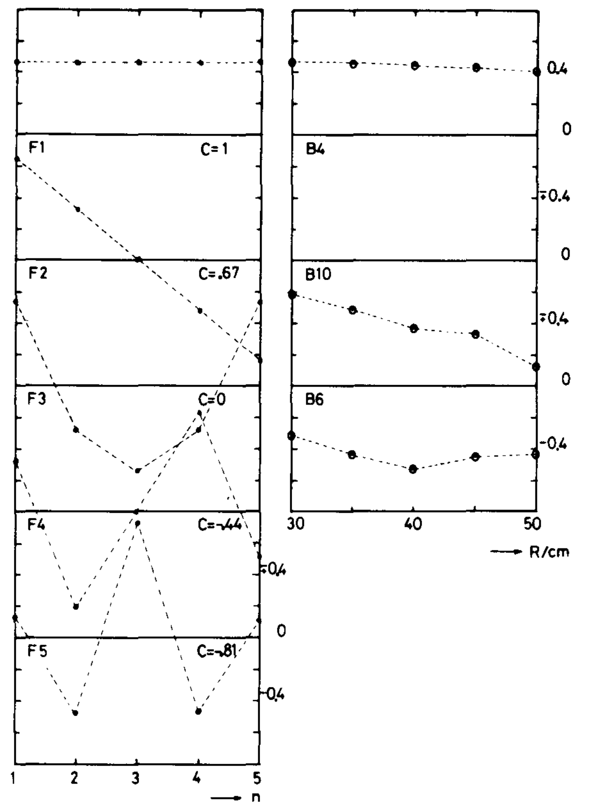


Fig. 2.1. On the left the normalized Chebishev polynomials for N=5 (F1...F5). These polynomials have, for increasing k, an increasing number of 'zero crossings' and a decreasing auto correlation coefficient c_k.
On the right the normalized 'parameter' base $\underline{\pi}_j$, corresponding with the concentric correction coils B4, B10 and B6.

TABLE I. The variation matrix A (deg/div) for the phase control loop at 20 MeV protons

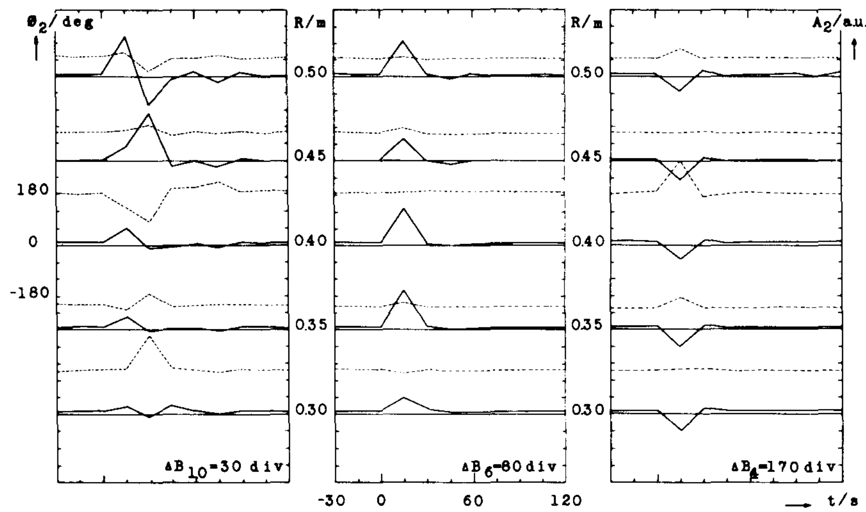
$$\begin{pmatrix} \phi_{30} \\ \phi_{35} \\ \phi_{40} \\ \phi_{45} \\ \phi_{50} \end{pmatrix} = \begin{pmatrix} 0.39 & -0.81 & -0.43 \\ 0.37 & -1.11 & -0.62 \\ 0.37 & -1.37 & -0.87 \\ 0.35 & -1.22 & -0.97 \\ 0.33 & -1.22 & -1.39 \end{pmatrix} \begin{pmatrix} B4 \\ B6 \\ B10 \end{pmatrix}$$

TABLE II. The projections of $\underline{\pi}_j$ on the Chebishev base $\underline{\mu}_k$

$\underline{\pi}_1$=B4	$\underline{\pi}_2$=B6	$\underline{\pi}_3$=B10	
0.998	-0.986	-0.936	$\underline{\mu}_1$=F1
0.050	0.116	0.351	$\underline{\mu}_2$=F2
-0.007	0.099	0.041	$\underline{\mu}_3$=F3
0.008	0.028	0.040	$\underline{\mu}_4$=F4
0.009	0.029	0.039	$\underline{\mu}_5$=F5

on the Chebishev base are given in table II (i.e. S^{-1} conform section 2).
The variation matrix is used already more than a year and repeated measurements didn't show signifi-

Fig. 3.1 The performance of the HF-phase control loop after stepwise alterations of B10 (≈400 μT), B6 (≈1 mT) and B4 (≈2 mT). The second harmonic HF-phase ϕ_2 (solid line) and the amplitude A_2 (dashed line) are plotted vs time, i.e. the number of iterations.



cant changes.
To demonstrate the performance of the phase control loop, typical reactions of the loop on stepwise alterations in the parameter settings of B4, B6 and B10 are given in fig. 3.1. The interval time between two iterations is 15 sec due to teletype output delays. The interval time can be reduced to 3 sec. The HF-phases generally take again there original prescribed values after two or three iterations (within ≈1° second harmonic).
Any appropriate phase path (phase as a function of radius) can be reached within 2°.
The influence of a particular phase path on several beam properties (e.g. the energy distribution of the external beam) has been studied.

3.2 The extraction optimization

As stated in section 2, the extraction optimization can be reduced into a problem with prescribed values. The derivatives of the quadratic relation between the external beam current and the magnetic induction of the four harmonic trim coils have to be measured continuously without disturbing the external beam seriously. Therefore small disturbances are applied on the parameter settings, corresponding with a variation of the first harmonic of the magnetic induction of ≈5 μT. The responses in the external beam current are smaller than the instability due to the ion source (≈1 %). For each parameter - the central harmonic coils A11 and A12 and the extraction harmonic coils A31 and A32 - these responses are measured by a correlation technique which suppresses constant and slowly varying components in the external beam current. The block schema of the measuring equipment is given in fig. 3.2.1.
The measured relations between the 'new' beam properties ($\partial I/\partial A_{ij}$) and the parameters are given in fig. 3.2.2. These figures clearly show that the assumption of a quadratic relation is only valid for a limited range of the parameters around the optimal setting (500 div). However, they are well reproducible and a constant variation matrix can be used (table III). Some not well defined off-diagonal elements are taken zero.
To demonstrate the behaviour of the control loop, the reactions on stepwise alterations of the parameter settings are given in fig. 3.2.3. The interval time

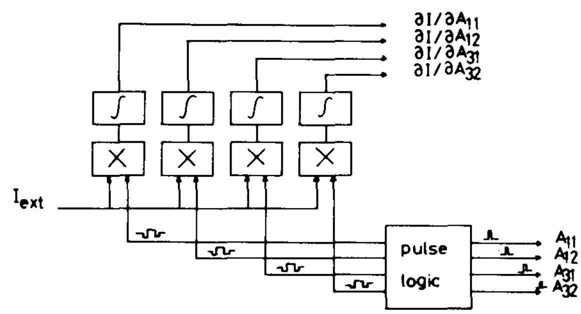


Fig. 3.2.1 A simplified block schema of the pulsing system for the extraction optimization. Small disturbances applied on the settings of the harmonic coils A11...A32 are correlated with the corresponding responses in the external beam current. The correlation products are proportional to the derivatives $\partial I/\partial A_{ij}$.

TABLE III. The variation matrix A (mV/div²) for the extraction optimization at 20 MeV protons

$$\begin{pmatrix} \partial I/\partial A_{11} \\ \partial I/\partial A_{12} \\ \partial I/\partial A_{31} \\ \partial I/\partial A_{32} \end{pmatrix} = \begin{pmatrix} 4.0 & 0.0 & 0.0 & -2.0 \\ 0.0 & 4.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 5.0 & -2.0 \\ -2.0 & 0.0 & -2.0 & 6.0 \end{pmatrix} \begin{pmatrix} A_{11} \\ A_{12} \\ A_{31} \\ A_{32} \end{pmatrix}$$

between two iterations is 40 sec. This rather long time, due to the correlation time constant needed, is however not too serious; small slowly varying deviations from the optimal settings will be corrected before a human operator can see it. Sometimes sub-maxima will be reached when starting too far away from the optimum.

3.3 The external beam guiding system

In the external beam guiding system, two control loops are installed:

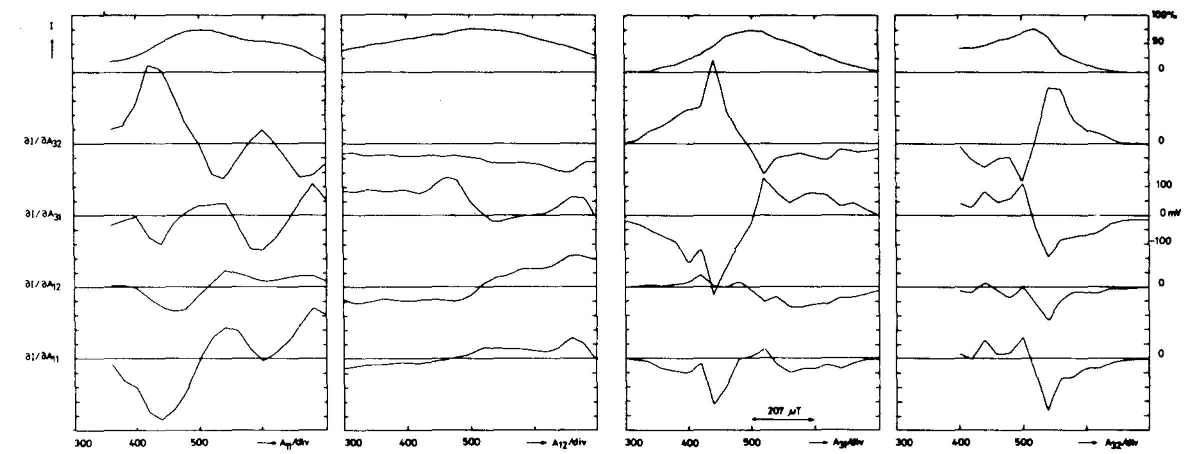


Fig. 3.2.2 The measured relations of the four derivatives of the external beam current vs the settings of the four harmonic coils. The slopes of the curves in the optima (500 div) correspond to the elements of the variation matrix A. The upper curves give the extraction efficiency.

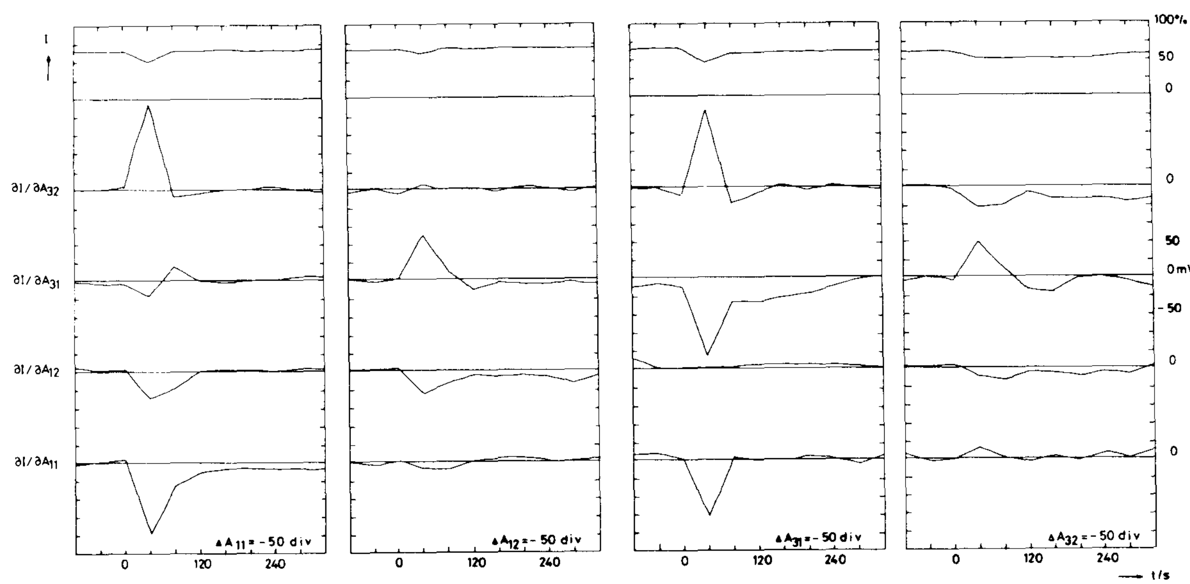


Fig. 3.2.3 The performance of the extraction efficiency control loop after alterations of the parameter settings corresponding to $\approx$-100μT.

1) the horizontal and the vertical position of the beam is measured using 26 pin-type DANFYSIK scanners. The relations between the beam positions and the settings of (small) bending magnets are linear, and the control schemes cf. section 2 are applied. The first manual control actions were carried out four years ago[6]. The loop will be electrically closed this year.
2) The magnetic induction of two 45° bending magnets in the energy analysing system are controlled using an intermittent NMR control system. Each magnet is controlled during 4 sec, while the other magnet has a fixed setting via a hold circuit. The accuracy is better than 10^{-5}. With this system, together with the HF-phase control loop, the relation between a particular phase path and the energy of the external beam has been studied.

We want to thank prof. H.L. Hagedoorn and prof. N.F. Verster for their many essential contributions.

References

1) F. Schutte, *On the beam control of an isochronous cyclotron*, Thesis EUT (1973)
2) F. Schutte e.a., *The automatic control of the Eindhoven AVF-Cyclotron*, Proc. of the VI Cycl. Conf., Vancouver, (1972)
3) J.F.P. Marchand e.a., *Suppression of odd harmonic components in a cyclotron beam pick up signal by means of sampling*, Rev. Sci. Instr. 45,3(1974)361
4) G.C.L. van Heusden e.a., *The HF-phase measuring system of the Eindhoven AVF-Cyclotron*, Proc. of the VII Cycl. Conf.,Zürich, (1975)
5) *Handbook of mathematical Functions*, Ed. M. Abramowitz and I.A. Stegun, National Bureau of Standards, Math. Series .55
6) F. Schutte e.a., *A method of matching the external beam of a cyclotron to an ion optical axis*, Nucl. Instr. and Meth. 97(1971)347