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EXTRACTION EFFICIENCY OPTIMIZATION FOR THE EINDHOVEN AVF CYCLOTRON

J.I.M. Botman, R.F. Kruis and H.L. Hagedoorn.

Eindhoven University of Technology, Eindhoven, The Netherlands.

Abstract.- This paper describes a substantial improvement of a control system which optimizes the extraction efficiency of the ion beam in the Eindhoven AVF cyclotron. The equipment used induces small perturbations in the currents of those coils with large influence on the extraction process. The responses in the beam current after extraction are correlated with the perturbing pulses. The system consists of CAMAC modules with some external electronics. The timing, of the measuring and perturbing equipment, is controlled by a programmable CAMAC clock. An important part of the measuring equipment is a fast data logger, that performs the measurements of the extracted beam current. The correlation is performed by a PDP11 computer. An on-line least-squares parameter estimation method (learning procedure) is applied, which is used to determine the control matrix for extraction optimization. The extraction optimization system corrects slowly varying changes in certain cyclotron parameters such as drift of the magnetic field, to preserve maximum external beam current.

1. Introduction.- The extraction of particles in the Eindhoven cyclotron is performed by means of an electrostatic extractor. Several parameters have an important influence on the extraction efficiency. Some parameters, for instance the extractor voltage, remain well constant during one shift of cyclotron operation, and do not need to be altered, once set. However, the extraction efficiency will not remain constant after optimization at the beginning of a beam shift. Changes in the extraction efficiency are primarily caused by drift in the cyclotron magnetic field, e.g. through temperature effects. We have found that reoptimization is best carried out by readjusting the current through the harmonic coils (the inner harmonic coils A_{11},A_{12} and the outer harmonic coils A_{31} and A_{32}) and the outer two concentric correction coils (B_8 and B_{10}).

A control system was designed for optimization of the extraction efficiency [1,2]. Small block shaped pulses are induced on the aforementioned correction coils, and the response in the external beam current is correlated with the perturbating pulse. The perturbation is limited by the requirement that the resulting changes in the external beam current remain below 1% of the total beam current, being the order of beam current variations due to ion source instability.

2. Principle of the control system. Figure 1 gives a general scheme of the control system. A pulse generator induces small perturbations on the parameters p_i (the currents through four harmonic and two concentric coils). The response of the external beam current I to these perturbations is proportional to the first derivatives $\partial I/\partial p_i$ around the optimum setting. From the derivatives $\partial I/\partial p_i$ the computer calculates the necessary changes in the parameter settings to optimize the extraction efficiency and carries them out via the control equipment. The beam current response is measured with a correlation method.

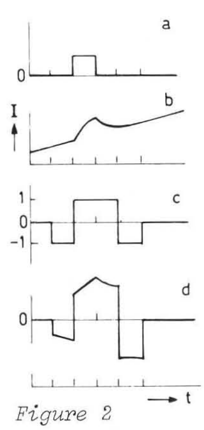

Figure 2

A schematic representation of the correlation method is given in figure 2. The response in the external beam current (b), due to a perturbing pulse (a), is multiplied with a so-called second order dorrelation pulse (c) to give a product signal (d), which is integrated in time, yielding a correlation product proportional to $\partial I/\partial p_i$. Due to the shape of the correlation pulse constant and linearly varying components in the beam signal will not contribute to the result.

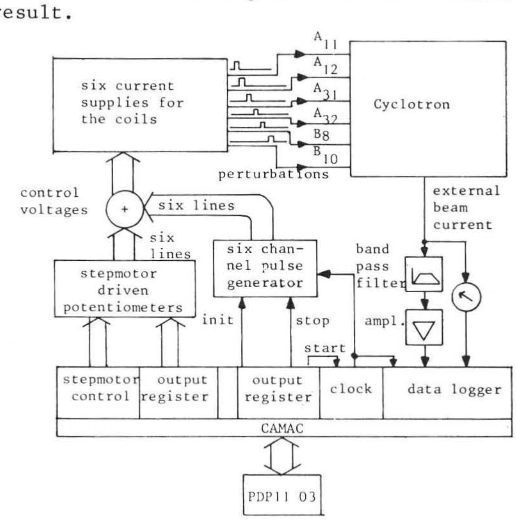

Figure 1 Block diagram of the control system.

Originally the correlation was performed with analogue correlators [2]. Presently, the external beam current variations are sampled by a transient recorder (datalogger) in CAMAC, and the correlation is performed by the computer by multiplying the samples with plus or minus one and adding them. This makes the correlation fast and more versatile.

3. Measuring and control equipment. - The heart of the system is a clock module (Le Croy 8501) in CAMAC, of which the number of pulses and the frequency of the

pulse train can be software programmed. This module drives a six channel pulse generator, as well as the datalogger (transient recorder, Le Croy 8212), of which the sample rate is equal to the clock frequency.

The pulse generator delivers successively a perturbing pulse at each of the output channels. The pulses are added to the control voltage of the considered parameters. Pulse duration and rest time after each pulse may be varied; we used 80 msec for pulse duration, 896 msec rest time for a concentric coil and 96 msec rest time for a harmonic coil. Figure 3 shows a complete measuring cycle. The difference in rest times arises from the fact that the time constant for the harmonic coils is ~ 0.2 s, and ~ 1.0 s for the concentric coils.

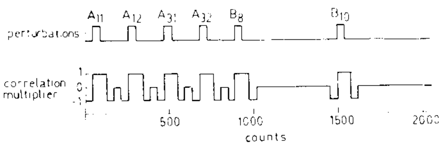

Figure 3 Schematic presentation of the perturbation and correlation timing for one measuring cycle.

The external beam current can be measured either with a beam stop target behind an experiment station or with capacitive pick-up probes. The DC level, slow variations and noise of the external beam current are filtered out for a major part by an 0.1 Hz to 20 Hz band pass filter. After that the signal due to parameter perturbations is amplified 5.10^4 times to bring it within the voltage range of the datalogger (± 5 V). A measure of the amplitude of the external beam current is logged separately to obtain information about the performance of the control system.

The sample rate of the datalogger was set to 500 Hz, while a pulse train of 2048 pulses was used for each measuring cycle. The samples are translated in 12 bit data and stored in a 32 K memory module (Le Croy 8800), organized as a circular shift register. The measurements stored in the memory module are read out by the computer via the datalogger after two complete measuring cycles. Then the aforementioned correlation can be performed. Necessary control actions are carried out via stepmotor driven potentiometers.

4. The on-line least squares method.- We denote the control parameters by a vector $\underline{p}$ with components p_i (i = 1, ..., 6), for coils A_{11} to A_{32}, B_8 and B_{10}. The maximum $\hat{I}$ of external beam current occurs for the settings $\hat{p}_i$, i.e.: $\hat{I} = I(\hat{\underline{p}})$. Small deviations from the optimum parameter setting: $\Delta\underline{p} = \underline{p} - \hat{\underline{p}}$ will cause a change in the external beam current $\Delta I = I - \hat{I}$. This may be approximated by a quadratic function of the deviations:

$$I = \hat{I} + \sum_i \sum_j a_{ij} \, \Delta p_i \Delta p_j \tag{1}$$

Differentiation with respect to p_i yields

$$r_i \underset{def}{=} \frac{\partial I}{\partial p_i} = 2 \sum_{j=1}^{6} a_{ij} \, \Delta p_j \tag{2}$$

which is written in vector notation as: $\underline{r} = \underline{\underline{V}} \, \Delta\underline{p}$

where the 6 x 6 matrix $\underline{\underline{V}}$ is called the variation matrix. Under working conditions the variation matrix turns out to be non singular, therefore the inverted equation reads:

$$\underline{p} = \underline{\underline{C}} \, \underline{r} + \hat{\underline{p}} \tag{3}$$

where the matrix $\underline{\underline{C}} = \underline{\underline{V}}^{-1}$ is called the control matrix. We use this relation in two ways. In the learning phase we take many measurements of $\underline{r}$ as a function of $\underline{p}$ with the pulse apparatus. By a least squares method we determine the unknown quantities C_{ij} and $\hat{p}_i$. Then we enter the stabilizing phase where we compensate the slow drift of the cyclotron : a measurement of $\underline{r}$ together with the known matrix $\underline{\underline{C}}$ gives the optimum as

$$\hat{\underline{p}} = \underline{p} - \underline{\underline{C}} \, \underline{r} \, . \tag{4}$$

Both phases overlap as the new measurements of $\underline{r}(\underline{p})$ can be used for a further improvement of the estimation of $\underline{\underline{C}}$.

The unknown quantities in the least squares problem are the 36 elements of $\underline{\underline{C}}$ and the 6 elements of $\hat{\underline{p}}$, adding up to 42 unknowns. This is inconveniently large as the numerical effort increases at least as the square of the number of unknowns. The matrix $\underline{\underline{C}}$ is symmetric, this reduces this number to 27. We cannot use this symmetry, however, as time constant effects in our pulse method give unknown scaling factors for the various derivatives r_i . These factors are moreover dependent on the value of the main field. Therefore we decided to ignore the symmetry of $\underline{\underline{C}}$. The eq.(3) can be written as six independent equations, each with 7 unknowns, for each component p_i. From now on we drop the subscript i for this component, and have thus:

$$p = \underline{C}^T \, \underline{r} + \hat{p}, \tag{5}$$

where $\underline{C}^T$ is the i^{th} row of matric $\underline{\underline{C}}$. So we have in fact six different equations of this type for the six values of i.

Eq.(5) has 7 unknowns. We perform a much larger number N of measurements than seven for different values of the parameter setting p, and determine the unknowns employing a least squares method. The measurements have to be sufficiently independent. We take the unknowns together in the system vector $\underline{s}$:

$$s = \begin{pmatrix} \underline{C}^T \\ \hat{p} \end{pmatrix} \tag{6}$$

We define the measurement vector $\underline{m}_n$ for measurement number n by

$$\underline{m}_n^T = (\underline{r}^T, 1) \; , \tag{7}$$

and define the deviation from eq.(5) as the error E_n:

$$E_n = p - \underline{m}_n^T \, \underline{s} \; . \tag{8}$$

The least squares criterion reads

$$\sum_{n=1}^{N} E_n^2 \text{ is minimal,} \tag{9}$$

with all measurements weighted equally.

The N vectors $\underline{m}_n^T$ are the rows of the so-called design matrix $\underline{\underline{M}}$ [3)]; the N parameter settings p_n form the observation vector $\underline{P}$. The least squares problem reads :

$$|\underline{P} - \underline{\underline{M}} \, \underline{s}|^2 \text{ is minimal for } \underline{s} = \hat{\underline{s}}. \tag{10}$$

This can be interpreted in $\mathbb{R}_N$ with the base vectors $\underline{e}_n$: $\underline{P}$ is a point, $\underline{\underline{M}} \, \underline{s}$ is a seven-dimensional surface. This surface is described by seven base vectors $\underline{M}_k$, the columns of $\underline{\underline{M}}$. The best value is the projection of $\underline{P}$ on $\underline{\underline{M}} \, \underline{s}$.

It should be remarked that the design matrix is the same for all the six values of i, which gives a drastic reduction of the numerical work involved.

Although the solution $\hat{s}$ of the criterion (10) can be given directly in terms of a matrix form of the matrix $\underline{\underline{M}}$ and the vector $\underline{P}$ [3], the required memory space may become prohibitive if the number of measurements increase continuously, which happens in our case. We have chosen a solution method proposed by Peterka and Smuk [4] to satisfy criterion (10), which has turned out suitable for the use of on-line computers. In this method the amount of memory space is independent of the number of measurements, and the calculation time is limited. After the addition of a measurement (increasing the dimension by one) a rotation of the axes $\underline{e}_n$ is carried out such that the seven dimensional surface supported by the vectors $\underline{M}_k$ lies in $[\underline{e}_1, \ldots, \underline{e}_7]$, while $\underline{P}$ lies in $[\underline{e}_1, \ldots, \underline{e}_8]$. In this new basis the number of rows of $\underline{\underline{M}}$ remains limited to 7 and the number of coefficients of $\underline{P}$ remains limited to 8.

A comparison of the amounts of memory space, and of calculation times for comparible least squares estimation methods is given by Schreurer [5].

5. The performance of the control system.- We present some measurements which were done for a 7 MeV proton beam cyclotron setting.

Figure 4 shows the response in the beam current to the perturbation in the four harmonic coils A_{11}, A_{12}, A_{31} and A_{32} and in the two concentric coils B_8 and B_{10}. The picture represents the read out of the data logger. Two complete measuring cycles are displayed. The parameters were deliberately set beside the optimum beam current to show a response to each perturbation.

The amplitude for the current perturbation was generally set to 0.2 A for the concentric coils and 0.15 A for the harmonic coils, which means a change in the magnetic induction of $19.2.10^{-6}$ T and $18.75.10^{-6}$ T respectively. The main magnetic induction for 7 MeV protons is 0.7 T.

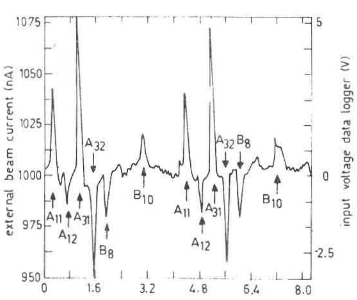

Figure 4
Example of the response of the external beam current to perturbations of the coil currents.

Figure 5 gives an example of the performance of the control system as a function of time. A control action is done every 40 seconds, but only when the correlation products are larger than a small threshold value. A first estimate for the control matrix was obtained from the learning procedure, by which successively the setting of a parameter p_i was changed a little, and by then measuring the correlation products $\partial I/\partial p_j$. Sometimes the control actions may not be quite perfect as is seen in the figure : the first 440 seconds the system based the control actions on the start matrix, which resulted in an oscillatory behaviour of $\partial I/\partial A_{31}$ and of A_{31}.

In this figure a new estimate for the control matrix at the time *1* was taken, in which all the previous measurements, including the oscillations, were incorporated. It is seen that the new control matrix gave more stable control actions.

After 920 seconds (time *2*) the setting of parameter A_{11} deliberately changed. The control system counteracts this change making the correlation products small again. At the same time other parameters are slightly varied, indicating that there are non-zero off-diagonal matrix elements in the control matrix.

The control system can correct parameter changes within several minutes.

Other examples of the behaviour of the control system in various situations are given in a report written by R. Kruis [6].

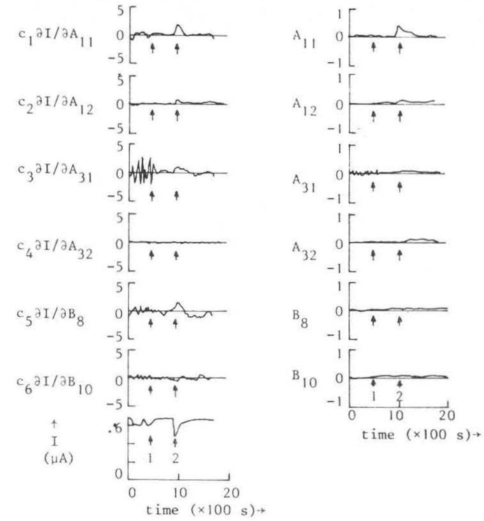

Figure 5
Correlation products $\partial I/\partial p_i$, external beam current I and potentiometer positions p_i as a function of time. The control system uses a first matrix C_1 until time 1 and after that a second matrix C_2. At time 2 A_{11} was changed from 8 div. to 50 div. The factors c_i are proportionality constants. The full range (-1, 1) of the potentiometer positions p_i in the figures at the right hand side corresponds to (-100, +100) potentiometer divisions.

Discussion

Possible improvements of the system can be made : A DC-free rectangular modulation pulse could be used as perturbing pulse. This can lead to a slight improvement in control time. The correlation may be performed with a sine function, which gives a slightly better signal to noise ratio. The sampling frequency and the ADC resolution are determined on account of the available hardware, in particular of the datalogger. The same performance could be expected from a system with substantially lower sampling frequency and lower ADC resolution.

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