THE AUTOMATIC CONTROL OF THE EINDHOVEN A.V.F. CYCLOTRON
I MEASURING EQUIPMENT

F. Schutte, L.C.J. Baghuis, H.L. Hagedoorn, D.M.J. Kroonenberg, J.F.P. Marchand
Eindhoven University of Technology, Eindhoven, Netherlands

ABSTRACT

For the automatic control of the Eindhoven A.V.F. cyclotron the HF phase angle, the intensity, the extraction efficiency and the horizontal position of the external beam before the magnetic channel are measured continuously and without interception of the beam. For this purpose the signals from capacitive pick-up probes are measured using sampling and correlating techniques.
With this experimental set-up intensities of 20 nA are measured and phase variations of 0.1 degree and position variations of 0.1 mm for a beam intensity of 10 μA have been detected.
The horizontal and vertical dimensions of the beam in the beam transport system are measured by means of a number of vibrating beam scanners with an accuracy of 0.2 mm down to intensities of 10 nA.
The relation between cyclotron parameters and beam properties is assumed to be linear for small variations and is represented by a matrix. Some of the matrix elements can vary slowly in time. They are measured continuously by pulsing the cyclotron parameters involved and correlating the beam response with the small perturbing pulses.
All measured data will be supplied to a PDP-9 computor via a CAMAC modular data handling system.

1. INTRODUCTION

The Eindhoven University of Technology A.V.F. cyclotron has been extensively described elsewhere [1,2,3]. It is a machine with a pole diameter of 130 cm, a bevelled 180° dee, a variable HF accalarating frequency (5...23 MHz), a threefold symmetrically magnetic field, 10 pairs of concentric correction coils ($B_1 \ldots B_{10}$), 3 pairs of harmonic coils ($A_{11} \ldots A_{32}$) and an electrostatic deflector at a radius of 52 cm. The beam transport system described in [4],and, with more recent data including 2nd order aberrations, in [5], has as main components an analysing part for doubly achromatic or dispersive modes of operation and a transport system to several experimental stations.
For the automatic control of the cyclotron a large number of beam properties are measured continuously without (serious) interception of the beam:

- the phase angle with respect to the HF dee voltage, internally and externally
- the intensity inernally and externally, yielding the extraction efficiency
- the horizontal position immediately after extraction
- the horizontal and vertical widths and positions and the intensities at a number of locations in the beam transport system
- the magnetic induction of the magnets in the analysing system, yielding the energy.

Capacitive pick-up probes are used for the measurement of the first three beam properties mentioned. For determining these properties we use sampling and correlation techniques. The electronic realisation is described in chapter 2.

The method of measuring the external beam properties is given in chapter 3.

It has turned out that the relation between cyclotron parameters and beam properties is linear for small variations [6]. This relation can be represented by a matrix. The elements of this matrix can be partly calculated or partly measured. Some of the elements will remain constant during cyclotron operation whereas others may vary slowly with time. The latter elements are measured continuously by pulsing the cyclotron parameters involved and correlating the beam response with the small perturbing pulses. The developed pulsing and correlating equipment is described in chapter 4.

2. CAPACITIVE BEAM PROBES AND MEASURING EQUIPMENT

The intensity of the internal beam and the phase angle with respect to the HF dee voltage can be measured with non-intercepting inductive [7,8,9] or capacitive [10,11,12] pick-up probes.

We use capacitive pick-up probes (so-called phase probes). They are located 1 cm above and below the median plane (fig. 1). The dimensions of the probes are 45 x 10 mm. The probes are situated at 8 different radii: 25(05)50, 42.5 and 47.5 cm. The latter two probes are inserted especially to control accurately the dependence of the HF phase angle on radius.

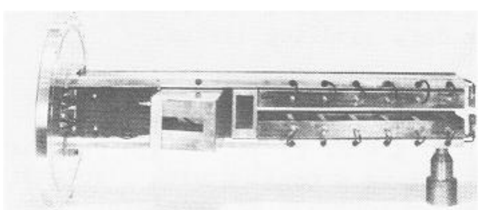

Fig.1 Capacitive pick-up probes (the probes at r=42.5 and 47.5 cm have been inserted later)

Two triangularly shaped probes are placed immediately after extraction at r=67 cm, above and below the median plane in order to measure the intensity, the phase angle, and the horizontal position of the beam. The dimensions of these so-called position probes are 125 x 55 mm. This type of probe has already been used in several laboratories [13,14]. The position of the beam is given by $x \propto (i_L - i_R)/(i_L + i_R)$, where i_L is the intensity of the left half and i_R stands for the intensity of the right half of the probe.

Fig. 2 shows the measuring equipment. The system consists of an HF part, a sampling device and an LF correlation part. Similar earlier

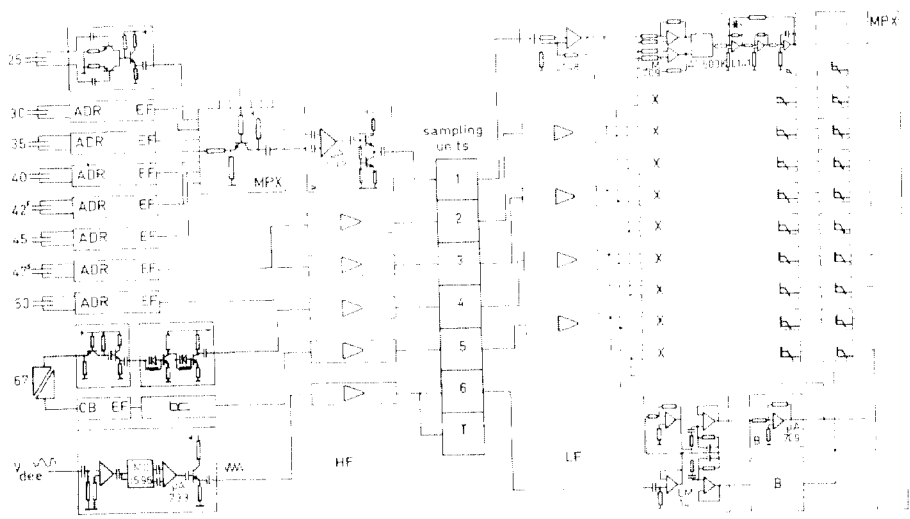

Fig.2 Electronic measuring equipment for detecting intensity, phase angle and horizontal position

experiments performed in our laboratory have been described in [15]. The signals of the corresponding upper and lower phase probes are added and via an emitter follower transported to a Tektronix sampling system. It consists of 3 dual input sampling units 3S2 and one timing unit 3T1 in a power rack 129. In this way we have 6 simultaneous sampling gates. One gate (No. 6) is occupied by the reference signal, being the frequency doubled dee voltage [7]. This reference signal also acts as a trigger signal for the sampling unit. The next two gates (Nos. 4 and 5) are fed with the signals from the two position probes. Finally, from the remaining 3 sampling inputs two (Nos. 2 and 3) are permanently occupied by two phase probes, while the last one (No. 1) is connected with the multiplexed signal of the phase probes left. Before sampling the position probe signals are led to a common base circuit and an emitter follower. These signals also contain a pick-up of the dee voltage. This pick-up signal is filtered by a two-stage tunable dee frequency filter. The signals are amplified to improve the S/N ratio of the sampling device. A characteristic signal from the position probe is given in fig. 3a.

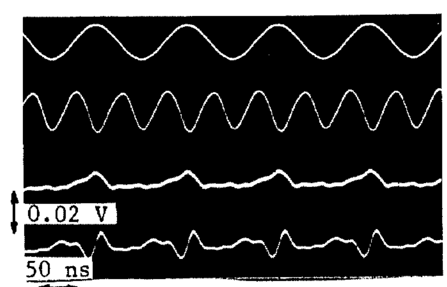

Fig.3a Signals before sampling

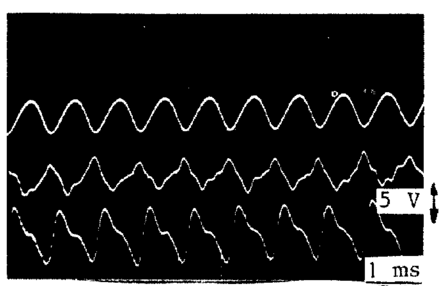

Fig.3b Signals after sampling

The signals from the phase probes are fed directly to the HF amplifiers since they are relatively large compared with the pick-up of the dee voltage. Fig. 3a also gives a signal from these probes.
By sampling, the HF signals are transformed to a frequency of approx. 1 kHz. The sampling frequency is about 30 kHz. The LF signals of a position probe and a phase probe are presented in fig. 3b. Note that the sampling takes place in such a way that only even harmonics of the dee frequency are allowed to pass through. This is realised by using an odd number of samples [16]. In this way of sampling the contribution of the (1st harmonic) dee frequency is reduced to negligable values. A consequence is that the periodicity of the beam signals is doubled (cf. fig. 3b).
In the LF part are determined the phase of the 2nd harmonic of the pulse with respect to the LF doubled dee frequency, and the intensity. Two signals with a phase difference of exactly 90 deg. are formed from the LF doubled dee frequency. After LF amplification the signals of the several probes are correlated with these two signals. This is performed with an AD530K multiplier (cf. fig. 2). Finally, the signals pass through two 3rd-order low-pass filters with variable damping and a cut-off frequency of 100 Hz and 1 Hz respectively. We now have for each probe signal two quantities, viz. $i_A=A\cos\phi$ and $i_B=B\sin\phi$. A measure of the amplitude of the (2nd harmonic of the) original signal (the intensity of the beam) is given by $i=(i_A^2+i_B^2)^{\frac{1}{2}}$. The phase angle between the 2nd harmonic of the original signal and the doubled dee frequency is given by $\phi=\arctan(i_B/i_A)$.
With this measuring set-up we are able to detect intensities of 20 nA. The accuracy in the phase measurements (1st harmonic) is 0.1 deg. at 10 μA and 1 deg. at 1 μA beam intensity. The position measurements can be performed with an accuracy of 0.1 mm at 10 μA and 1 mm at 1 μA beam intensity. Some results obtained with the equipment are shown in part II [17].

3. EXTERNAL BEAM PROBES AND MEASURING EQUIPMENT

The horizontal and vertical dimensions of the beam in the beam transport system are measured continuously by means of a number of vibrating beam scanners. These scanners (manufactured by Danfysik, Jyllinge, Denmark) consist of a tungsten wire of 0.75 mm diameter, vibrating at 14 Hz through the beam (fig. 4). The top-top amplitude is 50 mm. The wire intercepts the beam twice per vibration period. The picked-up current is fed to a current-voltage convertor (fig. 5). The output voltage is amplified in order to deliver a signal which is integrated to determine the beam intensity, and is at the same time put into a peak follower and a comparator. The comparator supplies a blocked pulse train (fig. 6). The duration of the pulses corresponds to e.g.

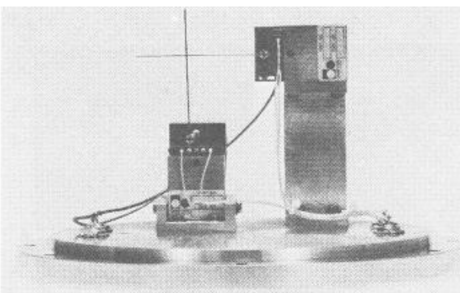

Fig.4 Beam scanners

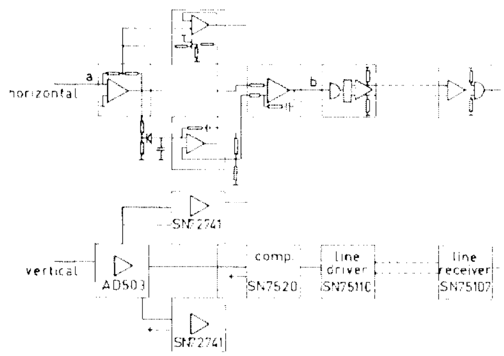

Fig.5 Electronic measuring equipment for beam scanner signals

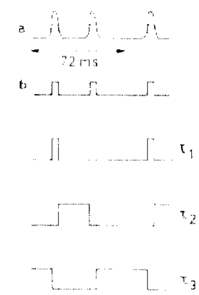

Fig.6 Beam scanner signal

the FWHM of the beam pulses, representative of the beam width, whereas the difference between two successive time intervals is a measure of the position of the beam with respect to the vibrating axis of the scanner. Finally, this train of pulses passes through a line driver, is transmitted via a twisted cable, and 'decoded' by a line receiver in the control room. Using a simple electronic device, mainly consisting of logic circuits, three different pulses τ_1, τ_2 and τ_3 are formed from the pulse train (cf. fig. 6). The pulses can either be fed into a digital counter or into the computor.
With the set-up described above we are able to detect beam widths and positions with an accuracy of 0.2 mm and a minimum beam intensity of 10...30 nA, depending on the measure of focussing at the location of the beam scanner involved.
The energy of the beam is determined by fixing accurately the magnetic induction of the two analysing magnets in the beam transport system. This is performed by means of an N.M.R. control on both magnets simultaneously. The N.M.R. measurement is carried out with a measuring and control unit manufactured by A.E.G.

4. PULSING OF CYCLOTRON PARAMETERS

Cyclotron parameters p_j have to be set so that a number of beam properties r_k have a desired value, while the remaining beam properties e_i are optimal. For small variations the relevant dependences are assumed to be linear. For the first type of beam properties we can therefore write

$$\Delta r_k = \frac{\partial r_k}{\partial p_j} \Delta p_j$$

for several k and j, which implies that $\partial r_k / \partial p_j$ is an element of a matrix. For the second type of beam properties we have to minimise

$$Q = \Sigma \, (e_i - e_{io})^2 \; .$$

Here e_{io} stands for the optimal value of the beam property e_i. This relation implies

$$\frac{\partial Q}{\partial p_j} = 2 \, (e_i - e_{io}) \frac{\partial e_i}{\partial p_j} = 0 \; .$$

$\partial e_i / \partial p_j$ are also elements of a matrix.

For the mathematical solution of the problem use is made of the method described in [18].

In the introduction we already stated that the matrix elements may be known either from numerical calculations or from measurements. They may be constant during operation (e.g. the horizontal position of the external beam as a function of the extractor voltage $\partial x/\partial V_{extr}$) or they may vary (slowly) with time, which means that they have to be measured continuously (e.g. the external beam intensity as a function of isochronism $\partial i/\partial B_{10}$).

For the automatic control we measure the most important of the last mentioned matrix elements continuously, viz. the external beam intensity as a function of the current through the central harmonic coils (A_{11} and A_{12}), the extraction harmonic coils (A_{31} and A_{32}) and two concentric correction coils (B_8 and B_{10}). For this purpose we introduce a small variation of short duration on these cyclotron parameters. This yields a response of the external beam intensity. The response contains information on the optimal setting of the relevant parameters. We developed a 6-channel pulse unit, which offers the possibility of adding a block-pulse shaped perturbation to the power supplies of the six cyclotron parameters mentioned. The amplitude and the duration of the perturbations as well as the time interval between two successive perturbations can be varied. This is realised in the following way (fig. 7).

From a 50 Hz pulse are formed two clock pulses, the first having a period of 40 ms and the second one of 320 ms. When gate i is opened the fast clock pulse is fed to counter A. The setting of this counter is a measure of the duration of the perturbing pulse to be generated. Considering it to be set at 3 (so the duration of the perturbing pulse equals 120 ms) it generates a stop pulse after 3 periods of clock 1. After 4 successive stop pulses, the last JK flip-flop closes gate ii and opens gate vii. Now counter B receives clock pulse 2. The setting of this counter determines the period of rest between the perturbation of the parameter involved and that of the next parameter. When this counter is set at e.g. 2, after two clock pulses (i.e. 640 ms) it resets itself and initiates counter A of the next channel. After the sixth channel has operated a new cycle may start.

Fig. 8 shows the timing of one channel. The pulses i and 1 form the perturbing pulse, which causes a variation in the voltage of the power supply of the cyclotron parameter involved (pulse m).

The pulse yields a response of the external beam intensity. To detect whether the setting of the parameter involved is optimal, this response is correlated with pulse r (cf. fig. 8), which is deduced from the perturbing pulse. This process acts as some sort of second derivative detection, as it eliminates the constant dc level or an unwanted drift of the beam intensity. The correlation is carried out by multiplier MC1595 (cf. fig. 7). The correlation product yields a measure of the correctness of the setting.

The variations in the parameters have to be so small that the relative variations in the external beam intensity are less than approx. 1 %, being of the order of the instability of the ion source. For this reason the above mentioned process is repeated continuously and the correlation product is integrated.

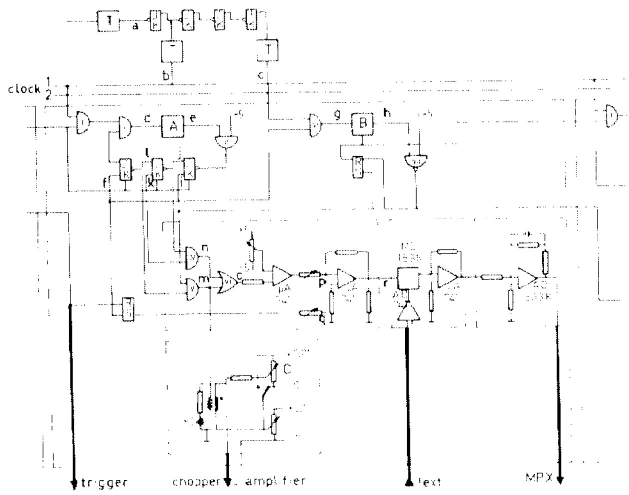

Fig.7 One channel of the pulse unit

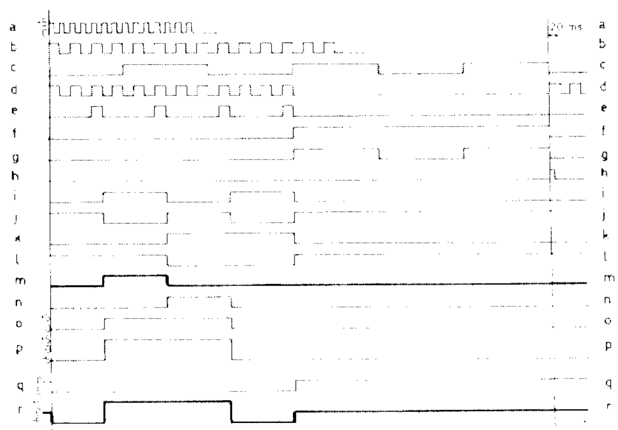

Fig.8 Timing of one channel of the pulse unit

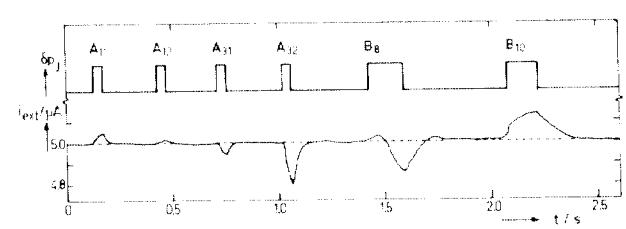

Fig.9 Possible responses of the external beam intensity on a perturbation of several cyclotron parameters

Fig. 9 gives an example of the response of the external beam intensity on a perturbation of the six parameters mentioned.

5. DATA ACQUISITION

All beam properties described in the preceding chapters will be submitted to the D.E.C. PDP-9 computor installed in our laboratory. For this purpose use will be made of the CAMAC modular data handling system [19,20,21]. The data will be transmitted to a number of Normal Stations in one Crate. They will be submitted to the Datachannel input mode of the PDP-9 via the Crate Controller A and the Branch Driver. The Branch Driver and the interface between that and the PDP-9 have been developed. The main part of the software, including the device handler, has already been written and tested. The complete system will be in operation at the end of 1972.

REFERENCES

1. N.F. Verster et al., *Proc. Int. Conf. on Sector-Focussed Cycl. 1962* Nucl. Instr. and Meth. 18,19(1962)88
2. N.F. Verster et al., *Proc. Int. Conf. on Sector-Focussed Cycl. and Meson Fact. 1963*, CERN report 63-19(1963)43
3. F.T. Howard, Isochronous Cyclotrons-1972 *Data sheets 6th Int. Cycl. Conf.*, Vancouver, Canada
4. H.L. Hagedoorn, J.W. Broer and F. Schutte, Nucl. Instr. and Meth. 86(1970)253
5. G.E. Sandvik, H.L. Hagedoorn and F.Schutte, to be submitted to Nucl. Instr. and Meth. (1972)
6. F. Schutte, K.R. Ehrnreich and G.C.L. van Heusden, Nucl. Instr. and Meth. 97(1971)347
7. H.P. Stüssi and F. Schutte, Nucl. Instr. and Meth. 89(1970)87
8. H.-H. Feldmann, thesis Technische Universität Berlin (1964)
9. Yu. N. Denisov, A.N. Lyubenko and P.T. Shishlyanikov, *Proc. 5th Int. Cycl. Conf.*, Oxford, Great Brittain, (1969)151
10. C.G. Dols, *Proc. Int. Conf. on Sector-Focussed Cycl. 1962*, Nucl. Instr. and Meth. 18,19(1962)595
11. W.H. White, B. Duelli and R.J. Jones, *Proc. Int. Conf. on Sector-Focussed Cycl. 1962*, Nucl. Instr. and Meth. 18,19(1962)601
12. J.K. Bird and R.E. Berg, *Proc. 5th Int. Cycl. Conf.*, Oxford, G.B., (1969)399
13. J.C. Marchais, M.Y. Romain and G. Rommel, l'Onde Electrique, 39(1959)582
14. W.A. van Kampen, thesis Technische Hogeschool Delft (1969)
15. L.C.J. Baghuis, Ned. Tijdschr. voor Nat. 37(1971)505 (in Dutch)
16. J.F.P. Marchand et al., to be submitted to Rev. Sci. Instr. (1972)
17. F. Schutte et al., *Proc. 6th Int. Cycl. Conf.*, Vancouver, Canada, (1972)
18. K. Halbach, *Proc. 2nd Int. Conf. on Magnet Techn.*, Oxford, G.B., (1967)47
19. EUR 4100, *CAMAC, a modular instrumentation system*, Euratom (1969)
20. EUR 4600, *CAMAC, organisation of multicrate systems*, Euratom (1971)
21. G.C.L. van Heusden et al., to be submitted to CAMAC bulletin (1972)

DISCUSSION

WEGNER: How do you get the digital data that you put on your curves from the analogue data that you displayed?

SCHUTTE: You have two signals, the A $\sin\phi$ and B $\cos\phi$, which give immediately, if everything is calibrated well, the intensity and phase. You just have to plot these against the cyclotron parameter you are varying and you get your data. Now if you would like to put them into the computer, you must, of course, digitize them. But that is obvious, you just have to put them into CAMAC.

WILLAX: You have an enormous amount of information on accelerator parameters gathered. Is your machine only available for this kind of investigation?

SCHUTTE: You would think so! One of the tasks of our machine is machine development in this way; we can use, and have used for the last two years, approximately 25-30% of beam time doing this type of investigation. We also work in the evenings and at night.

CRESSWELL: I wonder if you could give me some indication of the bandwidth of the system you describe and how near, for instance, you place the front-end electronics to the transducers--the transmission mediums you use to maintain the bandwidth and so on, sensitivities.

SCHUTTE: The bandwidth should be at least 100 Mc. From the sampling system it is 1 Gc/sec, and we have rather short cables down to the cellar where the high-frequency amplifiers and the tunable filters are installed, and then after that you just have the cable up to the system.

CRESSWELL: Yes, what I am trying to find out, in fact, is what is the overall bandwidth of the system--not the sampling system which is 1 Gc/sec, I suppose--but the overall system bandwidth.

SCHUTTE: It will be 100 Mc/sec.