Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

NON-INTERCEPTING ION PHASE MEASURING EQUIPMENT OF THE ISOCHRONOUS CYCLOTRONS AT KARLSRUHE AND JÜLICH

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Abstract

A non-intercepting ion phase measuring equipment is in use at the Karlsruhe cyclotron. Five phase signals, steadily and simultaneously displayed are presenting a good survey of phase width and phase distribution versus radius. High noise immunity is obtained by the use of differential electrostatic pickup probes.

Concerning the Jülich cyclotron a similar device with twelve double electrostatic probes is in construction.

Introduction

Regardless of the geometrical configuration of the accelerating system the energy gain per turn of the ions in a cyclotron is always proportional to the cosine of their phase o, referred to the accelerating voltage. Maximum energy gain is obtained when the particles pass the bisecting line of the accelerating sectors just at the moment the polarity of the r.f. voltage is changing ($\phi = 0$).

To accelerate the ions up to maximum energy it is necessary to properly adjust the exciter currents of the trim-coils in such a way that on all orbits the condition $\cos \phi > 0$ is maintained.

Severe demands will have to be made to the accuracy of the field when one should try to obtain separate orbits in the cyclotron. In this case the energy gain of the particles of each ion bunch must not diverge more than n to (n+1) where n is the number of orbits considered. To obtain this an extreme narrow phase width and an isochronous field shape of utmost accuracy is necessary.

Proper adjustment can be achieved by the method of Garren and Smith[1], or by using a movable phase probe. But these methods require plenty of time as the influence of any trim-coil-current is not restricted to a definite area of the field and can hardly be predetermined.

Phase Measuring Equipment of the Karlsruhe Cyclotron

The cyclotron at Karlsruhe is equipped with a device to simultaneously display five beam phase signals on a cathode-ray tube (CRT) using five double electrostatic pickup probes. The probes are mounted at the outer edges of five trim-coil groups which are placed concentrically in such a way that every group covers the same number (abt.5o) of orbits (s. Fig. 1). Means are provided to regulate the frequency of the accelerating voltage in dependence of the phase signals. But, hitherto, there was no need to close the control loop. It is not difficult for the cyclotron operator to carry out slight field corrections from time to time on the base of the phase display.

Sampling Technique

In order to examine all details of phase signals the transmission and display system of the equipment must have a frequency response of about $1o^9$ cps. Because of the recurring wave forms the information transmitted is very small but covers an extremely wide frequency spectrum.

The favourite method to reduce the redundance of a recurring wave form is the sampling technique. By a very fast switch a small portion of each of the steadily recurring wave forms is selected and stored until the next sample has been taken (s. Fig. 2). The switch consists of a gate controlled by the strobe pulse in such a way, that the transposed signals of the same wave form but of much lower frequency are built up by the stored samples. Only the input circuit must suffice the wide band width of the signals.

Beam phase measurements in a cyclotron were primarily carried out by M. Konrad in the Birmingham cyclotron, reported in 1958[2]. He used a beam catching probe and applied the sampling technique. Some years later, commercial sampling oscilloscopes, were available on the market and it became easier now to make phase measurements in cyclotrons. Employing commercial sampling oscilloscopes beam phase measurements were made on the isochronous cyclotrons at Berkeley and Oak Ridge[3,4]. In both cases a movable phase probe was used, in Berkeley a beam catching water-cooled target, in Oak Ridge an electrostatic probe attached to an experimental target.

Signal Pickup Methods

A non-intercepting pickup method takes off the phase signal from the electromagnetic field accompanying the ion bunches. Fig. 3 shows three suitable methods. The first and second method (Figs. 3a and 3b) is less expensive by using commercial sampling oscilloscopes. In both cases the displayed signals are differentiated and do not correspond to the charge in the neigbourhood of the probe but to its temporal change.

On the other hand the third method (Fig. 3c) is more expensive, but produces a true image on the CRT of the charge in the neighbourhood of the probe. It is characterized by the fact that the induced voltage on the plate of the probe is directly transposed in a low-frequency voltage by a sampling gate G. This method is used for the phase measuring equipment of the Karlsruhe cyclotron. It is relatively simple to extend the system to a great number of probes. Each probe only requires a sampling gate G and a low-frequency display channel, easily obtained by an electronic switch connected with the input of the CRT. The sampling gates G are simultaneously controlled by the common strobe pulse generator P. How moderate the expense is may be seen in Fig. 4 from the circuit diagram and in Fig. 5 from the construction drawing concerning to a probe as used at the Karlsruhe cyclotron.

Signal/Noise Ratio

When using the sampling technique, the sensibility of the pickup method is entirely unessential for the selection of this method. In this case only the ratio between the received beam signal and r.f. noise voltage is decisive. The disturbing r.f. field consists of standing waves excited by the accelerating voltage and especially its harmonics. Because of vertical asymmetries in the accelerating system considerable voltages are often set up between the pole plates.

The analysis of these problems leads to an important equation in which the useful signal/noise ratio of the m a g n e t i c field component H_s/H_n is compared with the e l e c t r i c field component E_s/E_n (s: signal, n: noise).

$$\frac{H_s/H_n}{E_s/E_n} = \frac{v}{c}$$

This ratio corresponds to the velocity of the particles v referred to the velocity of light c. When the directional characteristic of magnetic probes is included, one will find that with respect to the signal/noise ratio electrostatic probes are superior to magnetic probes, provided that the velocity of the particles is smaller than $\frac{2}{\pi}c$.

By using a non-intercepting pickup method there is no possibility to effectively screen the probe against the r.f. field especially against the harmonics of higher order. It seems to be the only way to lower the r.f. pickup by noise suppression in a differential pickup probe as shown in Fig. 6. While the ion bunch I induces signals of the same polarity on both plates P, the r.f. pickup has an opposite polarity. By using the third pickup method characterized by direct signal conversion (s. Fig. 3c) the r.f. noise voltage is simply suppressed by adding the low frequency output of both probes. By this way, in the phase measuring equipment of the Karlsruhe cyclotron the r.f. pickup is lowered so much that phase signals are well displayed down to 1 μA of the average beam current.

Width and Amplitude of the Signals

The theoretical analysis of the pickup problems permits the determination of the signal wave forms. Here it is usefull to approximate the distribution of the charge in the ion bunches as an error integral (e^{-x^2}) and to express the width of the bunches and their signals as the half width $\Delta\phi$ (band width at 50 % down).

The calculated curves in Fig. 7 permit to determine the width $\Delta\phi$ of the bunches out of the width $\Delta\phi_s$ of the displayed signals for the five probes. The calculation is based on a width of 39 mm for the pickup plates and a distance to the beam plane of 13 mm as

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the significant geometrical parameters.

In Fig. 8 the calculated peak voltage $\hat{U}$ is plotted versus the orbit radius r at different phase widths $\Delta\Phi$. The voltage is referred to an average beam current of 1 μA at Φ = 0 deg. and is based on an earth capacity of the pickup plates of 16.5 pF. Due to the radial increase of the charge density in a cyclotron the signal peak voltage $\hat{U}$ increases linear to the radius, as long as the ion bunches are smaller than the pickup plates (s. curve $\Delta\Phi$ = 5 deg. in Fig. 8). In contrary to this true display the pickup method of Fig. 3b gives a square and the method of Fig. 3a even a cube dependence.

Fig. 9 shows the frequency spectrum of the pickup voltage on the five probes referred to a phase width of $\Delta\Phi$ = 0 and $\Delta\Phi$ = 1o deg. The diagram reveals that the sampling device must have a band width of more than $1o^9$ cps to give a display without remarkable distortions.

Block Diagram of the Equipment

In Fig. 1o the simplified block diagram of the phase measuring equipment of the cyclotron at Karlsruhe is reproduced. The five differential probes combined with the sampling gates are mounted in the vacuum chamber. Nearby, the loop to take off the r.f. reference voltage is installed. At the outer side of the chamber a small box (s. Fig. 1) houses the low frequency differential amplifiers, the strobe pulse generator and the sampling gate for the reference voltage.

The 5-channel electronic switch and the horizontal deflecting voltage generator are contained in the control room together with the frequency converter, which produces the strobe pulse frequency.

As it is possible to generate the horizontal deflecting voltage out of the r.f. reference voltage by an equal sampling system, a zero phase balance is obtained which is independent from frequency changes. By this means the error of absolute phase measurements is less than ± 3 deg.

Examples of Phase Measurements

Two examples of phase measurements carried out with the equipment of the Karlsruhe cyclotron are discussed here.

The oscillogram in Fig. 11 demonstrates a simple method to check the zero phase balance of the equipment. The frequency of the accelerating voltage is shifted above the resonance so that near the fifth probe all ions change from accelerating to decelerating state (Φ = 9o deg.). Loosing their energy they return to the ion source. Hereby double signals are generated which must cover at all five probes, if orbits are centered and zero phase balance of the equipment is exact.

Fig. 12 consists of six oscillograms representing the phase distribution when the exciter current is changed considerably only in one of the five trim-coil groups. It may clearly be seen that a current change in one of the coil groups does not only produce a phase jump at the respective probe but also phase shifts in the opposite direction at the other probes. The phase measuring equipment of the Karlsruhe cyclotron enables exact necessary field corrections in a very short time, as the knobs for the currents of the five trim-coil groups are mounted directly below the CRT and adjustment can be made under immediate observation of the five phase signals.

Phase Measuring Equipment of the Cyclotron at Jülich

The cyclotron at Jülich will be equipped with a similar phase measuring device. Due to the higher maximum energy varying between 45 MeV and 9o MeV 12 double electrostatic probes are provided in this case. They are mounted at the outer edges of 12 concentric trim-coil groups, consisting of 36 pairs of coils. Each pair is fed by a DC push-pull amplifier. By means of analoque computer technique the amplifier inputs are coupled in such a way that first harmonic and isochronous field corrections can be carried out independently and are nearly restricted to the respective concentric trim-coil ranges. Important pre-requisites are thus met to control the isochronous field shape by the phases of the ion bunches automatically, so that it seems to be advisable to provide appropriate control loops.

References

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2. M. Konrad, Rev.Sci.Instr.29(1958)84o.
3. C.G. Dols, Nucl.Instr. and Meth. 18, 19(1962) 595-6oo.
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DISCUSSION

Follows next paper.

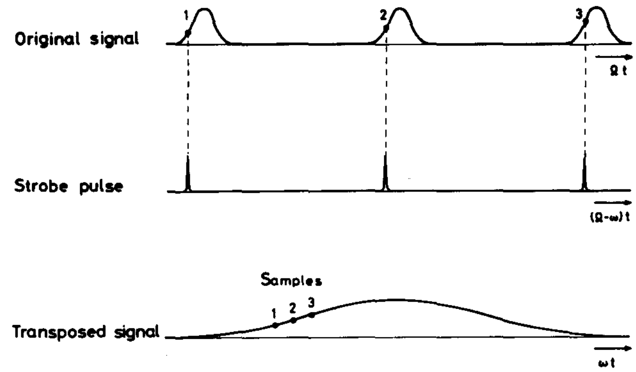

Fig. 2

Demonstration of the sampling technique.

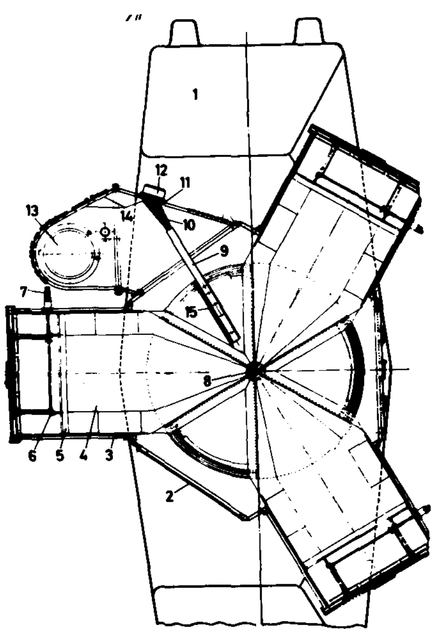

Fig. 1

Horizontal cross section of the Isochronous Cyclotron at Karlsruhe.

9 lower part of the phase probe containing five electrostatic pickup plates
1o coaxial lines
11 leading-through flange
12 amplifier box
15 carbon screen

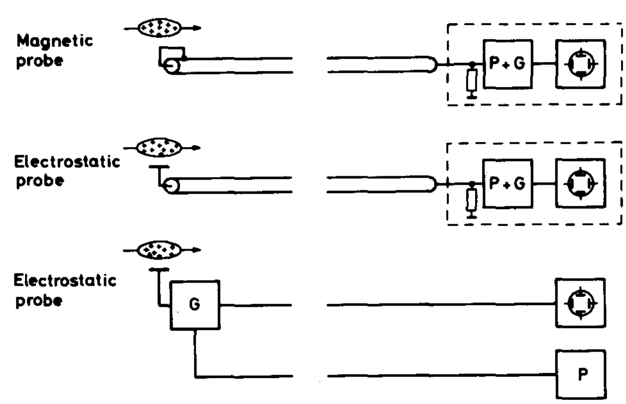

Fig. 3

Beam signal pickup methods.

a) Magnetic probe in connection with commercial sampling oscilloscope
b) Electrostatic probe with commercial sampling oscilloscope
c) Electrostatic probe with direct signal conversion by a special sampling system

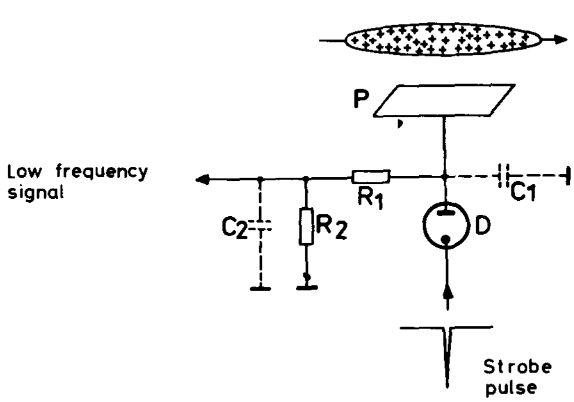

Fig. 4

Circuit diagram of the sampling gate.

P pickup plate
D gate diode
C_1 storage capacitor
R_1 and C_2 low-pass filter
R_2 load resistor

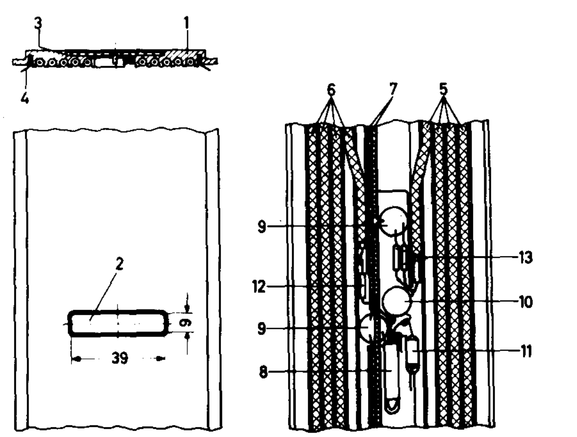

Fig. 5

Construction drawing of one of the pickup units.

1 carrier, 2 pickup plate, 3 insulator, 4 spring contact, 5 strobe pulse lines, 6 low-frequency lines, 7 heater voltage lines, 8 gate diode, 9 and 1o capacitors, 11 and 12 resistors.

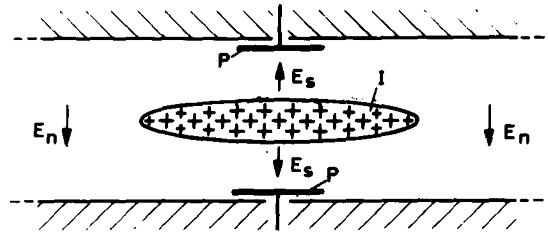

Fig. 6

RF-signal suppression by differential pickup probe.

I ion bunch
P pickup plates
E_s field strength of signal
E_n field strength of noise

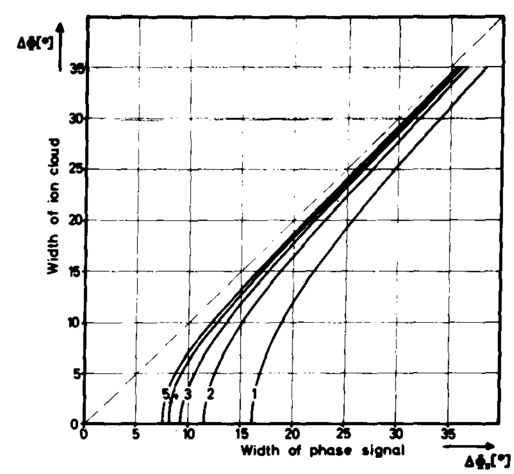

Fig. 7

Width of ion bunches $\Delta\phi$ vs. width of phase signals $\Delta\phi_s$ referred to the five probes.

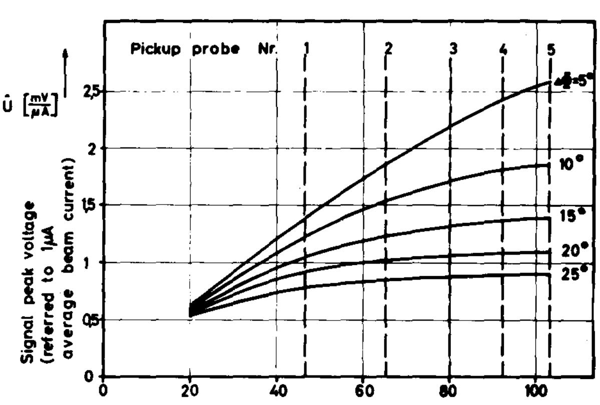

Fig. 8

Signal peak voltage $\hat{U}$ vs. orbit radius r in dependence of phase width $\Delta\phi$.

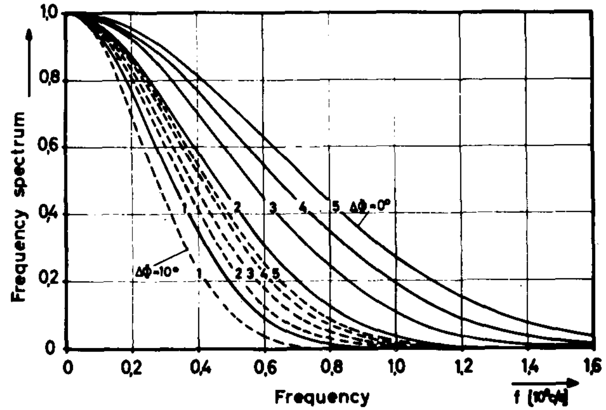

Fig. 9

Frequency spectrum of the pickup voltage of the 5 probes in dependence of phase width $\Delta\Phi$.

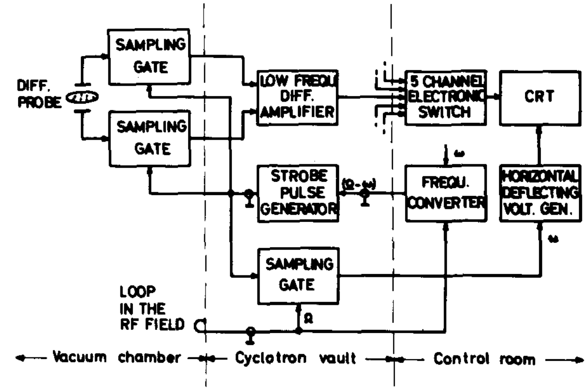

Fig. 10

Block diagram of the phase measuring equipment.

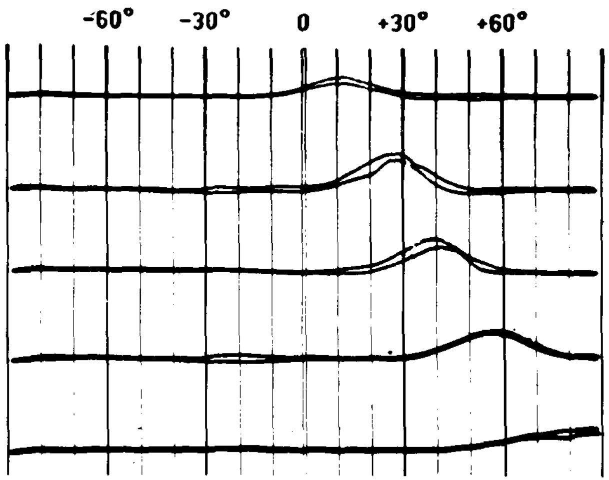

Fig. 11

Beam phase signals of ions in a state of acceleration resp. deceleration. The frequency of the accelerating voltage is shifted above the resonance.

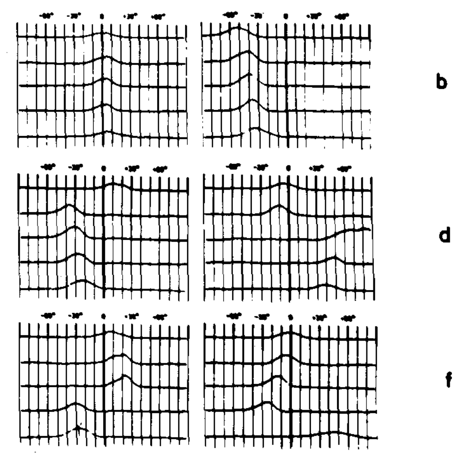

Fig. 12

Beam phase depending on the current distribution in the trim-coils.

a) exact adjustment
b) current in the first coil group too high
c) current in the second coil group too high
d) current in the third coil group too low
e) current in the fourth coil group too high
f) current in the fifth coil group too low