BEAM PHASE DETECTION WITH A FIXED INTERMEDIATE FREQUENCY SYSTEM AT JULIC

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ABSTRACT

In order to measure the beam phase in the cyclotron at low beam currents, a system has been developed which works well even in presence of severe HF-disturbance. By mixing and filtering techniques two fixed high frequency signals are derived and fed to a phase detecting circuit formed by double balanced mixers. Using a fixed frequency and applying a double compensation of the HF-disturbances, the system is able to analyse beam signals of less than 10^{-3} of the disturbing voltage. The capacitive phase probes are built in 50 ohm technique, which in principle allows the extension of their azimuthal length up to the optimum value. A special real time display of the beam phase and the intensity on a scope are provided.

1. Introduction

One requirement to achieve the best possible external beam quality from cyclotrons is a precise tuning of the isochronous field. A sensitive indicator for a correctly shaped field is the phase angle between the internal beam pulses and the accelerating HF-voltage. The old phase detecting equipment at JULIC based on the sampling method, which was developed by Feldmann[1)], turned out to be very unreliable and bad in sensitivity as well as in precision. Therefore it was necessary to develop new phase measuring equipment especially adapted to the situation at JULIC. After careful comparative studies of various phase detecting methods[2-5)] and extensive measurements at the cyclotron, we decided to realize a system based on real time frequency analysis method. We had to overcome an extremely bad ratio of beam signal to HF-disturbance picked up by the probes. Therefore we introduced signal processing on a fixed intermediate frequency to simplify the necessary narrow band filtering.

2. Relevant Cyclotron Features

The HF-frequency at JULIC is tuned between 20 and 30 MHz for a corresponding energy variation between 22.5 and 45 MeV/nucleon. The frequency stability of the self oscillating HF-generator of $\mp 1.5 \cdot 10^{-5}$ is of importance for the choice of the filter band width to be used in the signal path.

Beam currents of up to 60 µA, which correspond to the maximum possible external beam intensity, have to be accepted by the phase measuring system. On the other hand, it is of interest to measure the beam phase at beam currents as low as possible, for instance in the case of nuclear spectroscopy experiments. It is especially difficult to meet this requirement in the JULIC case. A Fourier analysis of the probe signals with and without beam (see figure 1) in the frequency tuning range revealed a bad situation, especially when taking into account that, for the results given in figure 1, a first compensation of the HF-disturbance was applied, as is explained below.

3. Measuring Principle

The signals are decoupled by electrostatic induction pick up probes mounted as usual above and below

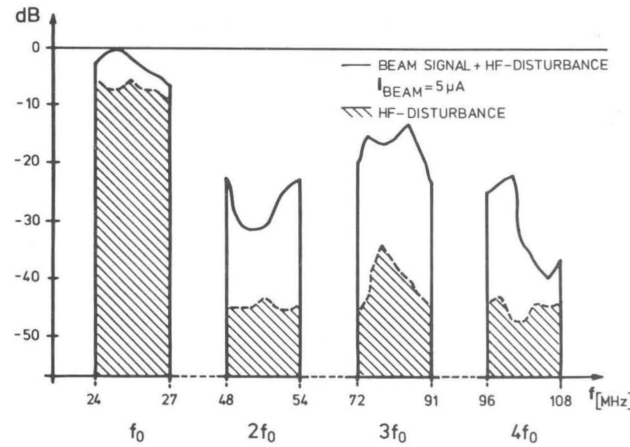
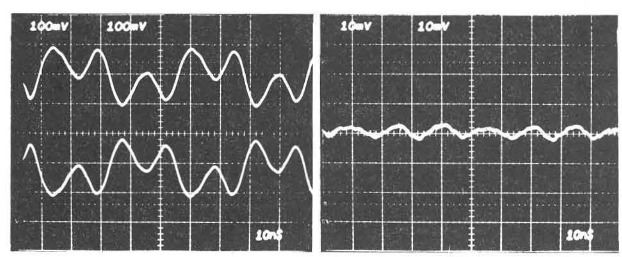


Figure 1: Beam signal and HF-disturbance

the median plane of the cyclotron. As the disturbing HF-signals of the upper and lower probes are opposite in phase but almost equal in amplitude, the addition of both signals is a first step to reduce the disturbing voltage (see figure 2). Since on the other hand, the beam signals are equal in phase, their output is therefore simultaneously doubled.



a b

Figure 2a: HF-signals picked up by upper and lower pick up probes (no beam)
2b: Signal after addition

Even though the beam signal to HF-disturbance ratio is on the average better for higher harmonics in our case (see figure 1), we decided to work on the second harmonic for the following reason: as the phase angle of the beam is multiplied by the harmonic number, the possible range of $-90^{\circ} < \varphi_{beam} < +90^{\circ}$ in the cyclotron is converted to $-180^{\circ} < \varphi < +180^{\circ}$, which can be detected directly without ambiguity. The multiplication of the cyclotron frequency to be used for reference is simple for second harmonic but more complicated in case of higher harmonic detection.

In the signal handling (see figure 3) we make use of the heterodyne principle to achieve a fixed frequency in the information channel as well as in the reference channel. Fixed frequency signal processing at

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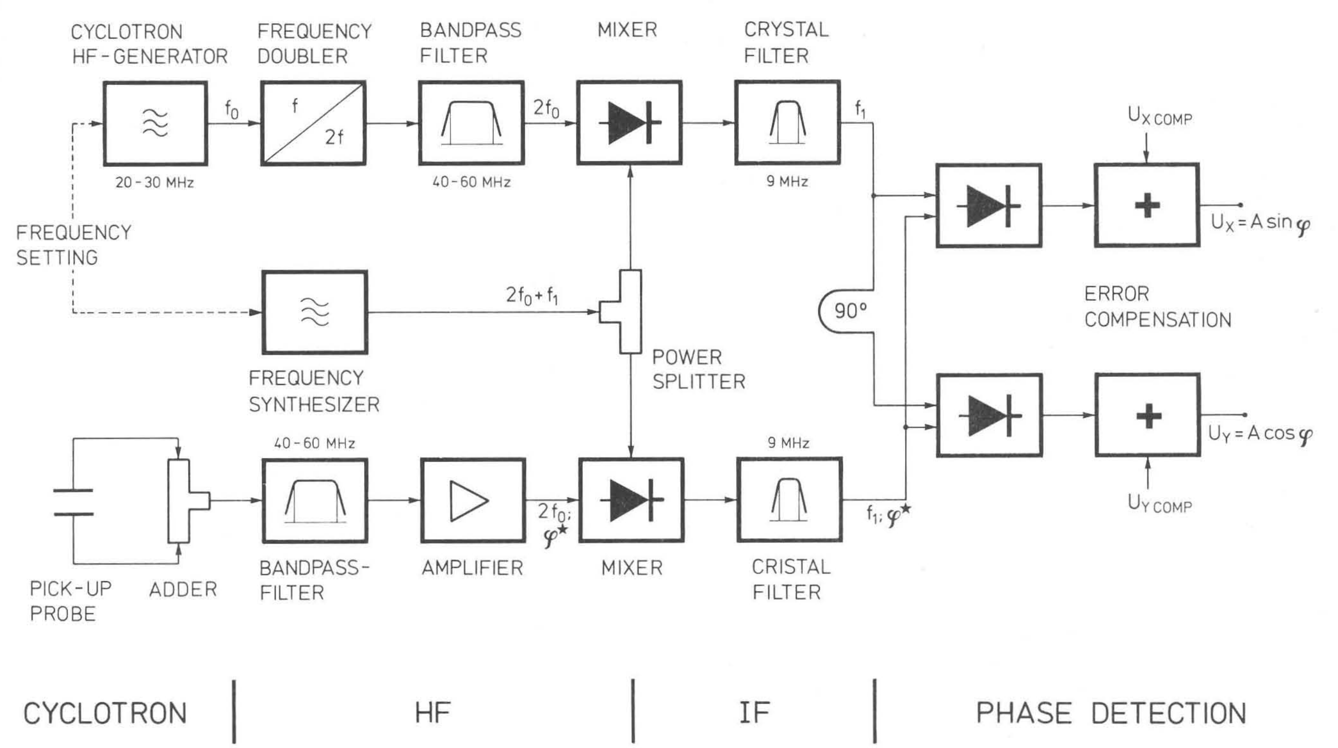

Figure 3: Block-diagram of the phase measuring system on the base of heterodyne principle

9 MHz is simple and well known from commercial radio receivers. Filtering in the intermediate frequency stages is performed by narrow band crystal filters, which remove all unwanted mixing products from the signal. The signals from the reference channel and the information channel are fed to a phase detecting circuit containing double balanced mixers. This circuit produces two DC-signals, which are the components of a vector in rectangular coordinates. This vector still has an inherent error, which is induced by the amount of the first harmonic of the accelerating voltage in the probe signal. This is compensated by tuning the DC-offset at each phase detector output to zero with the internal beam switched off.

4. Hardware Realization

The beam phase measuring equipment has been built into several modules using the AEC-NIM system. The circuit design of the HF-section was based on commercially available HF-components as power splitters, double balanced mixers, frequency doublers and amplifiers. Special band pass filters for the desired frequency range and amplifiers for signal and impedance matching have been developed in our laboratory.

4.1 Phase Probes

The probes are located along the centre line of one hill sector on the isochronous trim coil plates of the magnet. They are radially positioned in such a way that the distance between subsequent probes covers the same number of turns. Upper and lower probes (12 each) are mounted in two supports, which can be easily taken out of the cyclotron for inspection and repair (see figure 4).

To avoid any signal reflection the electrostatic pick up probes have an impedance of 50 ohms allowing in principle the extension to the optimum azimuthal value. Figure 5 shows a drawing of a probe together with the measured impedance along the probe, including the transition from the coaxial cable to the strip line. In our case we were restricted in reaching the optimum value because of some watercooling channels on the surface of the trim coil plates.

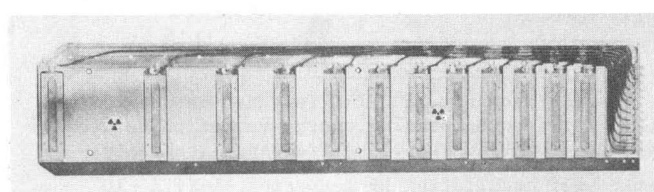

Figure 4: Support with 12 probes

Cables from the corresponding upper and lower probes have been matched in their electrical length with a time domain reflectometer to tolerances of less than 1 mm to avoid any phase shift before addition takes place. The signals are added by power combiners, which are directly mounted to coaxial feedthrus at the vacuum chamber. To avoid radiation damage of semiconductor devices, the signals are sent without amplification to the control room along a distance of about 40 m. We use semi-rigid cables to achieve the best possible shielding.

4.2 HF- and IF-Section

A HF-reference signal is decoupled from the accelerating system (see figure 3) and, after limiting to a fixed amplitude, fed to a frequency doubler. The following band pass filter removes all harmonics nf_o except $2f_o$. In a double balanced mixer this

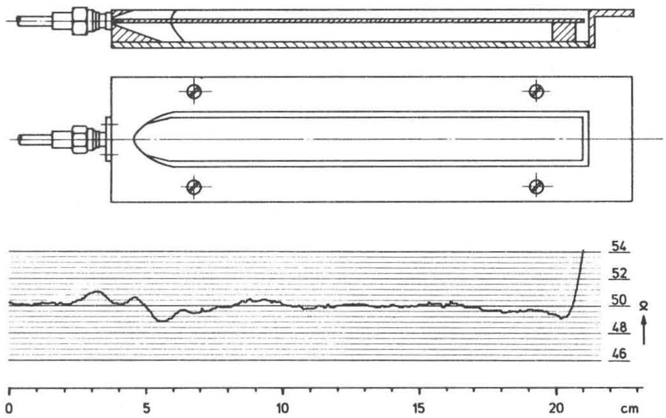

Figure 5: Design drawing of the 50 ohms pick-up (above) together with a corresponding display of the impedance (below)

signal is mixed with a signal $2f_o + f_1$ from a frequency synthesizer, which is programmed in such a way that its output signal is always f_1 = 9 MHz above the doubled cyclotron frequency $2f_o$. The mixer output is filtered by a narrow band crystal filter optimized in bandwidth for the residual frequency modulation of the accelerating voltage. An input band pass filter in the information channel passes only the desired harmonic in the range of 40 to 60 MHz. After a 40 dB amplification, the information signal is processed in the same way as in the reference channel.

4.3 Phase Detection

The phase detecting circuit is formed by double balanced mixers. In order to achieve the phase vector in rectangular coordinates, the reference signal has to be fed to one mixer directly and to the second one with a phase lag of 90°. Due to the fixed intermediate frequency it is possible to realize this phase shift by a simple piece of cable. The mixers used for phase detection were chosen to have a sufficient dynamic range as well as a good DC-stability. Both output DC-signals of the mixers are amplified by 20 dB and then fed to a compensation circuit. The phase detector output signals still have an inherent error, which is induced by the amount of second harmonic of the accelerating voltage picked up by the probes. Compensation is achieved by adding an appropriate DC-voltage with the internal beam switched off. The good stability of the circuits allows the cancellation of disturbing signals, which exceed the beam signal by a factor of 1000.

4.4. Readout Electronics

The scheme of the readout section is given in figure 6. The idea is to display a vector on a scope providing phase as well as intensity information on the internal beam. In order to cover the dynamic range of the HF-section, the gain of the input amplifiers of the vector display electronics can be set in the range of 1 to 5000 in steps of 1, 2, 5,... . Subsequent low pass filters are inserted for optional suppression of the jitter on the phase information due to the residual frequency modulation of the cyclotron HF. The cut off frequency of these filters can be switched to 0.1 Hz, 1 Hz or 30 Hz. The following circuit permits the rotation of the vector in the range of 0° to 360° without affecting the vector length. Thus the vector can be turned to any azimuthal position on the screen, which simplifies the readout. The vector generator combined with a multiplexer allows the simultaneous display of three independent phase vectors as well as an additional marker and the base lines of a rectangular coordinate system. The marker is introduced to facilitate the precise determination of the vector angle. It can be rotated manually to any azimuthal position, while its angle is read from a digital display with a resolution of 0.1°.

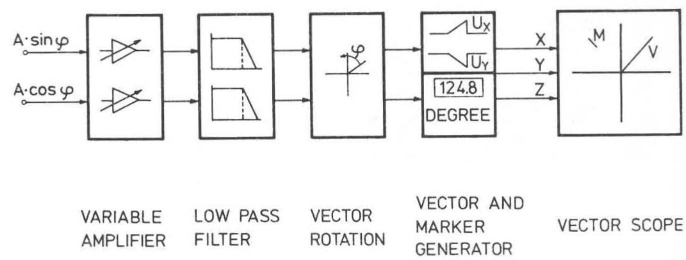

Figure 6: Block-diagram of readout electronics

5. Results

Three complete detection channels are now in operation. Test measurements have been performed at each channel. The input signals from the HF-source (HP 8640B) were frequency modulated with 15 Hz and a frequency deviation of ∓400 Hz to simulate the frequency instability of the cyclotron. The dynamic range was measured to be 80 dB corresponding to a lower and upper limit of approximately 0.3 μV and 3mV, respectively. At the lower limit the error of the detected phase angle becomes excessive (see table 1); the upper limit is determined by the output capability of the amplifiers. Since the sensitivity of the phase probes has been measured with the cyclotron beam to be 100 μV/μA (second harmonic), this range corresponds to 3nA $< I_{beam} <$ 30 μA. It has to be noted that there is a sensitivity increase in case of non modulated input signals. The inherent drift of the apparatus has been measured to be 6° maximum in beam phase angle in half an hour at the lower limit. In practical use at our cyclotron the above mentioned sensitivity is not achievable due to instabilities of frequency and amplitude, as well as non-ideal shielding.

INPUT-VOLTAGE [μV]	CORRESPONDING BEAM-CURRENT [nA]	U_X [mV]	U_Y [mV]	$\sqrt{U_X^2 + U_Y^2}$ [mV]	PHASE-ANGLE [...°]
0.16	1.6	0.4	0.05	0.4	7.1°
0.5	5	1.45	0.33	1.48	14.2°
1.6	16	4.6	1.15	4.74	14.0°
16.0	160	46.0	11.5	47.4	14.0°
160.0	$1.6 \cdot 10^3$	465.0	115.0	479.0	13.9°
$1.6 \cdot 10^3$	$1.6 \cdot 10^4$	$4.8 \cdot 10^3$	$1.2 \cdot 10^3$	$4.97 \cdot 10^3$	14.0°

Table 1: Dynamic range of the system (without preamplification at the probe)

By detuning the frequency or (for test) the magnetic field, the tip of the phase vector writes a cardioid pattern (see figure 7), if the beam phase along radius was already optimized[6] and a beam probe is positioned radially just behind the phase probe. Near the zero phase (as shown in the lower part of figure 7) the vector only changes its angle. Approaching the ∓90° phase deviation (upper part of figure 7, right or left pattern) the vector length increases because of a higher beam current density due to decreasing energy gain. By further detuning the phase, the particles start to get decelerated radially before the probe and the vector finally vanishes forming a straight line. This line shows the ∓90° phase angle, thus allowing calibration of the zero phase.

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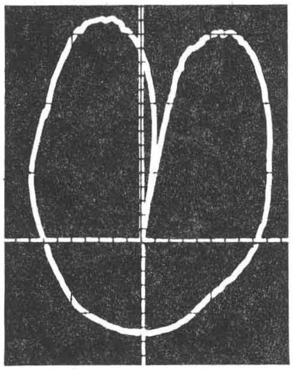

Figure 7: Cardioid pattern written by the tip of the phase vector together with coordinate system

6. Concluding Remarks

A possibly advantageous modification of the system is the application of double frequency conversion[7] as shown in figure 8. The expensive frequency synthesizer is replaced by a fixed-frequency oscillator and the residual FM is removed from the information signal, thus yielding possibly an improved sensitivity.

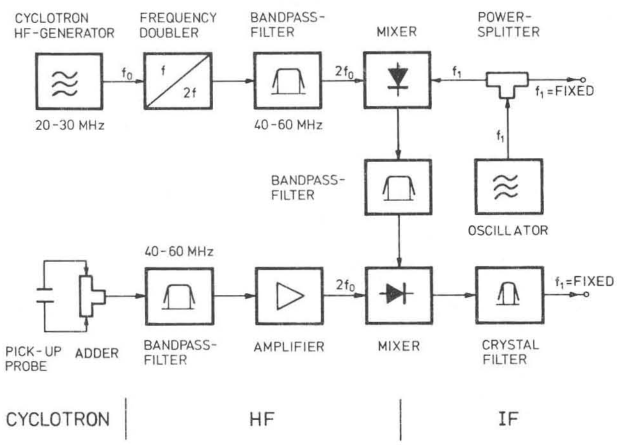

Figure 8: Block-diagram of an alternative phase measuring system based on heterodyne principle and double frequency conversion

References

1. H. H. Feldmann, Rückwirkungsfreies Meßverfahren für den Innenstrahl eines Isochron-Zyklotrons, Techn. Universität Berlin, Thesis (1964)

2. G. C. L. van Heusden, On the Computer Control of the Eindhoven A.V.F. Cyclotron, EUT Thesis Eindhoven (1976)

3. J. F. P. Marchand et al., Suppression of odd harmonic components in a cyclotron beam pick-up signal by means of sampling, Rev. Sci. Instr. 45 (1974)

4. F. Schutte, On the beam control of an isochronous cyclotron, EUT Thesis, Eindhoven (1973)

5. H. P. Stüssi and F. Schulte, A Method of Measuring the Phase Angle of a Charged Particle in a Cyclotron, Nucl. Instr. a. Meth. 89 (1962) 87-91

6. J. Reich, R. Brings, J. Linz, P. Wucherer, Beam Quality Improvement at JULIC, these proceedings

7. G. C. L. van Heusden, Private Communication, (1977)

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