BEAM STABILIZATION BY EXTERNAL BEAM-PHASE FEEDBACK

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Abstract

The phase of the external beam with respect to the R.F. accelerating voltage of the Michigan State University Cyclotron is measured using a capacitive phase probe located in the beam line. The beam is stabilized with a feedback-circuit that reduces phase variations by adjusting the main magnetic field of the cyclotron. The damping factor of the system is about 20.

1. Introduction

The object of the phase-feedback system described below is to increase the stability of the external beam of the Michigan State University AVF variable energy cyclotron.

The phase of the external beam (with respect to the R.F. accelerating voltage) is continuously measured with a capacitive type beam probe, mounted in the beam-line, and a phase detector. When the cyclotron is in a proper operating condition and the operator activates the feedback circuit, the actual beam phase will be stored in a memory; deviations in phase from this value will then cause a corrective action by varying the magnitude of the main magnetic field of the cyclotron. Provisions are built in the feedback circuit to suspend operation in case the external beam disappears, which would occur with R.F. sparks, etc. The next paragraphs describe in more detail the various elements of the system and obtained results.

1.1 The beam probe

A magnetic- and a capacitive-induction type beam probe have been built and tested. Evaluation of both probes favored the capacitive type because of its superior signal to R.F. noise ratio, when mounted in the beam line. The probe (Fig. 1) consists of a short cylinder with length of 5 cm and a diameter of 2.8 cm, aligned in the center of the beam-line, so that the beam can pass through. The charged particles of the beam will induce a voltage, which is amplified by a preamplifier mounted on the housing of the probe. This amplified signal consists of a pulse-like voltage, representing the beam current, superimposed on a sinusoidal noise voltage, induced by the R.F. system. This signal is then routed through a variable frequency (14-25 MHz) notch filter, for attenuation of this R.F. noise, and another amplifier, both located in the cyclotron vault. The total amplification of this chain is typically 50 dB. The bandwith (3db) is about 100 MHz. The amplified signal is

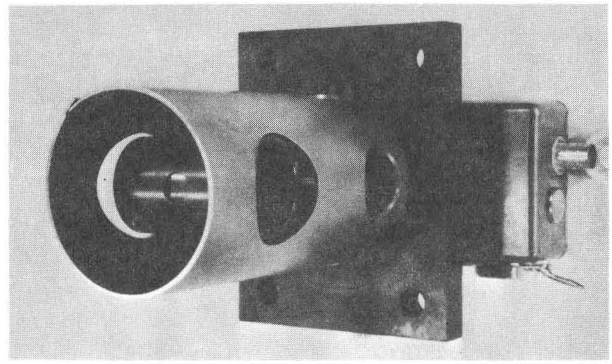

Fig. 1.--Capacitive phase-probe with preamplifier.

routed to the control room with a 50 Ω coaxial cable. A typical signal at this point is shown in Fig. 2.

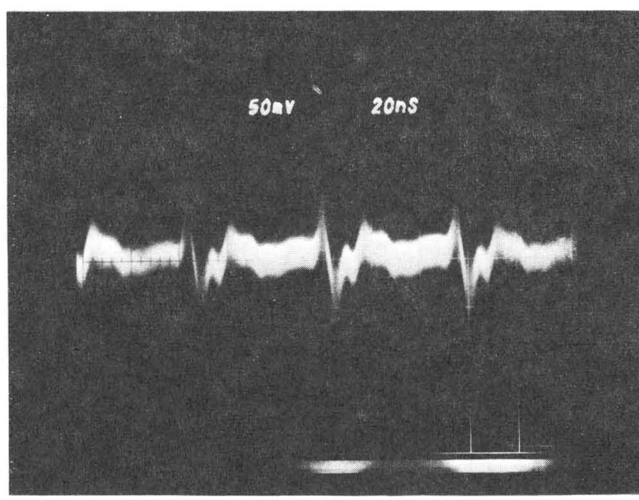

Fig. 2.--Typical signal from the phase-probe for a beam current of 0.6 A.

1.2 The phase detector

The phase detector (Fig. 3) is a combination of a zero-phase error detector and a R.F. phase-shifter network integrated in a feedback loop. The incoming signal V(t) is periodically sampled with gate S at time.

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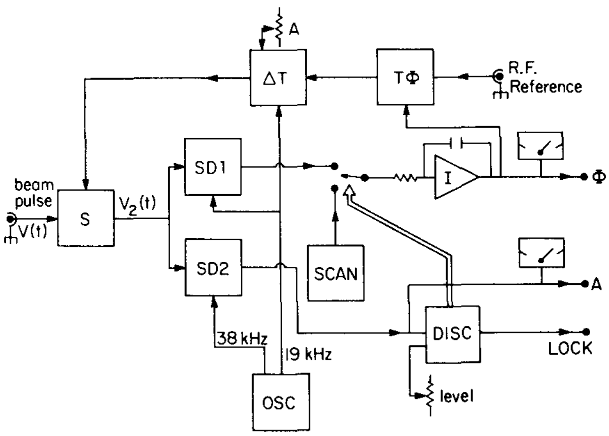

Fig. 3.--Block diagram of the phase-meter.

$$T_S = T_0 + T_\phi + \bar{A}\ \Delta T \sin \omega_1 t \qquad (1)$$

T_0 = Reference time

T_ϕ = Variable phase delay

$\bar{A}\Delta T$ = Scanning width

ω_1 = Scanning frequency (19 kHz)

Thus, a certain time slot in the R.F. cycle, with position T_ϕ and width $A\Delta T$ relative to a fixed position T_0 in the cycle is scanned at a frequency ω_1 (see Fig. 4). During

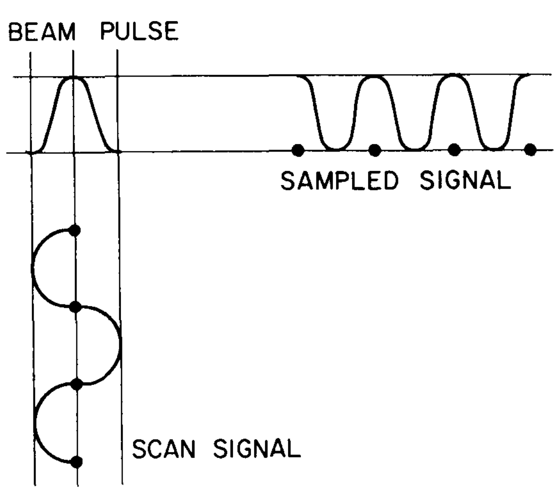

Fig. 4.--Sampled signal as function of scan signal.

normal operation of the detector this time-slot will contain part or all of the beam pulse. If the Beam pulse is centered in this time slot, the signal after the sampling (V_2(t) will have a periodicity of twice ω_1 (38 kHz) and an amplitude related to the amplitude of the beam pulse. After detection in synchronous detector SD 1, with the 19 kc signal as reference, a zero output will be obtained. If the timeslot is not centered around the beam-pulse, however, signal V_2(t) will contain a component of frequency ω_1 (19 kHz) and the output of detector SD 1 will not be zero. This error signal is integrated in integrator I. The output voltage of I is the reference signal of the variable-phase shifter ϕ. The error signal at SD 1 will thus cause a change in T_ϕ, and cause mentioned timeslot to be centered around the beampulse.

The output voltage of integrator I is interpreted as the beam-phase.

Synchronous detector SD 2 measures the amplitude of the signal V_2(t) by correlating it with a frequency $2\omega_1$. This signal is considered to be the amplitude of beampulse, e.g. the beam intensity. This amplitude signal is compared with a preset value at discriminator D. If the amplitude is below the preset value, it is assumed that no pulse exists in the time slot. This allows to discriminate against spurious pulses of lower amplitude. In this case, relay R will be activated, and the whole phase spectrum will continuously be scanned, until a pulse is found, in which case a lock signal L will go true. The two output signals, ϕ and L, are routed to the feedback circuit.

1.3 The feedback circuit

The feedback circuit has two functions: (1) holding the desired value of the phase-signal ϕ in an analog memory, and correcting the main magnetic field if there is a deviation from this value; (2) inhibiting operation if lock signal L goes false, in which case the value of signal ϕ is meaningless. About 1 sec after the phase detector becomes locked onto a signal the operator can turn on the feedback. This delay is initiated to insure the beam has stabilized. Upon turn-on, the signal ϕ will be stored in an analog register. The value of the voltage is stored in a digital form, in order to insure long-term stability. If now the value of the phase changes, an error voltage will be generated, and the main magnetic field will be corrected. If for some reason the phase detector becomes unlocked, the correction voltage existing about .5 sec. earlier than this event will be held. This function is implemented with an analog delay line and another analog memory. The .5 sec. delay is provided in order to protect against transcient effects at beam-loss time.

About 1 sec. after the phase-detector locks in again the feedback operation will resume. The regulation of the main magnetic field is obtained by varying the current through trimcoil TC8, a circular trimcoil with a large radius, rather than by varying the current through the main magnet coil.

The DC field-shapes of the two coils are very similar, but the frequency response, defined as a field-change in response to a current-change, of TC8 makes this coil a much better feedback element.

1.4 Results

Most of the testing of the apparatus has been done with beam intensities of about 1 μA external beam through the beam probe, with both protons and α-particles. The equipment will operate with intensities down to a few tenths of this intensity however. A damping factor of about 20 can be easily obtained without introducing instabilities in the feedback loop. The damping factor is understood as being the ratio of change of the beam phase as function of the main magnet excitation when the feedback is in operation and when it is not. As for the long term stability it appears that the phase-meter does need some improvement. Figure 5 is a composite figure of a) the measured phase without regulation, b) with regulation and c) the stability of the phasemeter, measured by introducing a reference signal of constant phase. This figure shows that the long term stability of the phasemeter itself is about 0.7° RMS, which is not much better than the stability of the cyclotron. The regulation of the phase is good to about 0.1° RMS. This suggests that with a better phase-meter the cyclotron can be stabilized to this figure. In first order the phase variation of the external beam is given by

$$d\phi = N*360\left(\frac{dB}{B}-\frac{d\omega}{\omega}\right) \qquad (2)$$

N= number of turns (210)

B=magnetic field

ω=accelerating frequency

Assuming the frequency is very stable a regulation of the external phase to 0.1° RMS corresponds to a regulation of the magnetic field of 1.4 ppm.

2. Conclusion

With a few improvements the described phase-feedback equipment can regulate the magnet of the MSU cyclotron to 1.4 ppm.

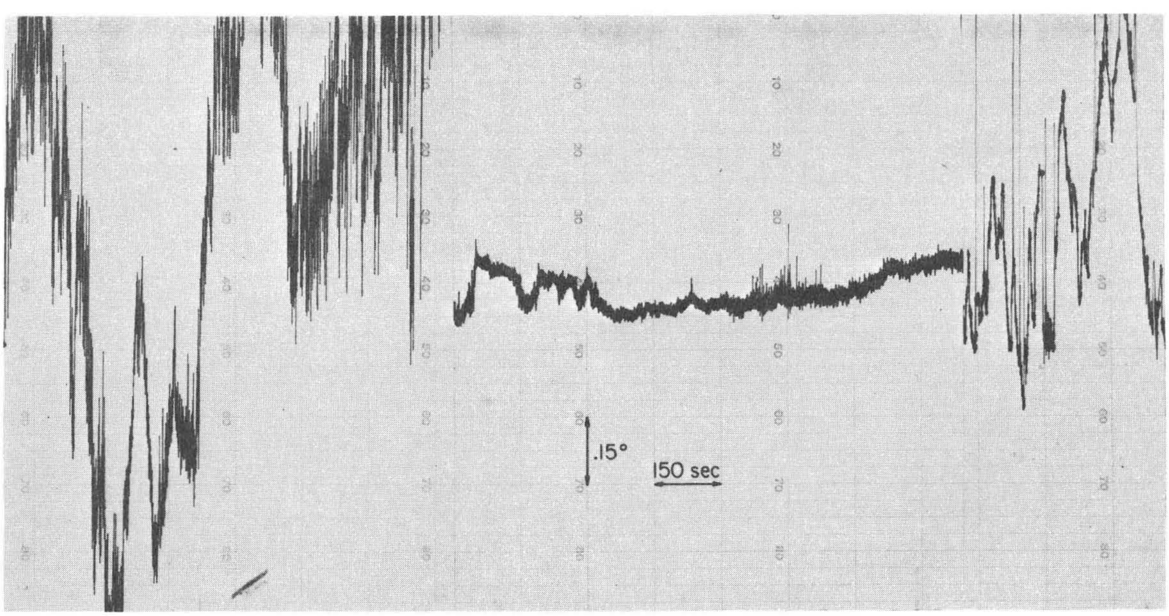

Fig. 5.--Phase stability as function of time. (a) Left: phase measured with unregulated cyclotron. (b) middle: regulated cyclotron. (c) right: The phasemeter itself.

DISCUSSION

G.C.L. VAN HEUSDEN: What is the minimal current at which the control loop can run?

P.S. MILLER: The lowest current is something around 200-300 nA at present.

G.C.L. VAN HEUSDEN: What is the time constant of the feedback loop?

P.S. MILLER: The time constant is of the order of a second.

Y. JONGEN: I am wondering how short is your pick-up electrode?

P.S. MILLER: The pick-up electrode is 5 cm.

Y. JONGEN: What is the axial length of the beam burst?

P.S. MILLER: The beam pulse is a little bit longer than that, the phase width is approximately 3 degrees

H.G. BLOSSER: I thought I would just comment that J.F.P. Marchand has a six day old daughter which has caused him to change his plans and not come to the conference.