MEASUREMENT OF INSTANTANEOUS VALUES OF VARIABLE MAGNITUDE IN PROTON SYNCHROTRON TECHNIQUE

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(presented by S. M. Rubchinski)

Summary

A description is given of the methods of measuring the instantaneous values of the magnetic field intensity (H_{inst}) and the frequency of radio-frequency oscillations (f_{inst}), both of which are of varying magnitudes. Nuclear magnetic resonance was used to measure H_{inst}, the accuracy being 1×10^{-4}. There are of three methods of measuring f_{inst}: selecting, "beating", and gating. The accuracy of the first two methods is better than 5×10^{-4} and that of the third method, 400 cycles.

In the measuring arrangement of the 10 Bev proton synchrotron of the Electrophysical Laboratory of the USSR Academy of Sciences, all these methods were applied.

In order to secure the effective acceleration of particles in proton synchrotrons it is necessary that the magnetic field intensity H at the magnet gap and the frequency of the accelerating field f change with time in strict conformity with the relation

$$f(t) = a \cdot H(t)/\sqrt{b + H^2(t)} = \varphi[H(t)] \qquad (1)$$

The practical solution of this problem required development of methods of dynamic measurement of the values H(t) and f(t), that is, of measuring the instantaneous value of varying magnetic field intensity (H_{inst}), and the instantaneous frequency (f_{inst}) of frequency-modulated oscillations, with an accuracy better than 10^{-3}.

When the correspondance of the instantaneous values f(t) and H(t) to the given law (1) is determined it is necessary to measure both values simultaneously. The following methods of measurement are available :

1. The pulse setting the moment of measurement turns on both f_{inst} and H_{inst} meters.

2. The pulse formed in the f_{inst} meter, with the given value of $f_i(t)$, turns on the H_{inst} meter.

3. The pulse formed in the H_{inst} meter, with the given value of $H_i(t)$, turns on the f_{inst} meter.

Which of the above three methods we choose in order determine the correspondance of the instantaneous values f(t) and H(t) to the law (1), depends on the methods adopted for measuring f_{inst} and H_{inst}. Thus, the first method is recommended if, at the output of both f_{inst} and H_{inst} meters, there is a counting possibility.

For measuring the instantaneous value of the varying magnetic field intensity we made use of nuclear magnetic resonance, a phenomenon widely applied for precise measurement of constant magnetic fields. At the output of the H_{inst} meter, there arises a short pulse excited by the voltage pulse which originates in the oscillatory circuit of the generator, the latter creating the so-called "weak high-frequency magnetic field".

The value $\dot{H}$ being sufficiently constant, the stability of this pulse with respect to the instantaneous value H(t) is better than 5.10^{-4}, and the magnetic field intensity ranging between 500 and 13,000 Oersted is easily measured.

To measure the instantaneous frequency of the frequency-modulated oscillations we made use of the following three methods : the method of selecting, based on the resonant properties of oscillating systems, the gating method, based on the time selection of figures which appear on the screen of cathode-ray tube, and the method of "beating" based on the specific transformation of voltages arising as a result of mixing, in two channels, the given constant frequency and the varying frequency that we are to measure.

These methods have been tested up to 10 Mc. The first and the third methods are characterized by a relative accuracy better than 5×10^{-4}. The absolute accuracy of the second method is 400 cycles.

When we study the effect of varying frequency oscillations on the oscillatory circuit with constant parameters, and when we investigate the phenomena of nuclear reson-

Fig. 1b. Experimental dynamic resonance curves.

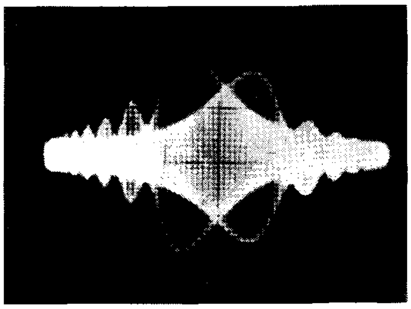

Fig. 1d. Nuclear resonance : experimental curve.

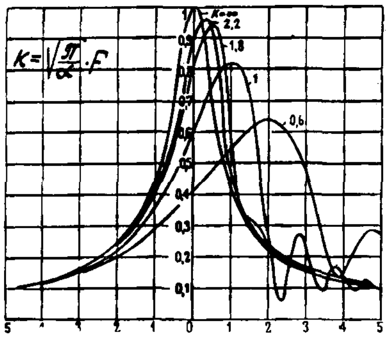

Fig. 1a. Theoretical dynamic curves in the resonance circuit with one degree of freedom (Bykova N.O.)
$K = \sqrt{\pi/\alpha}\ \ F$
F — statistic passband.
α — rate of frequency change.

ance in a varying magnetic field, we get dynamic resonance curves of a similar nature[1,2,3].

This can be explained by the fact that in the first case the electromotive force with varying frequency acts on the resonance system with fixed frequency, whereas in the second case the system with varying resonance frequency undergoes the influence of the force that has a constant frequency.

Dynamic resonance curves for both cases, obtained theoretically and experimentally, are represented in fig. 1 a and 1 d.

1. Measurement of the instantaneous value of the magnetic field intensity H_{inst} by the method of nuclear magnetic resonance

We have already said that for measuring H_{inst} we used the nuclear magnetic resonance impulse excitation produced by a given instantaneous value of the magnetic field intensity.

Fig. 2 shows a block-diagram of the measuring device. The impulse at the output of the device arises not at the moment when the condition of the resonance $\omega = \gamma H$ is fulfilled (where ω is the frequency of Larmor precession and γ the gyromagnetic ratio), but somewhat later, when magnetic field intensity is $H + \Delta H$. The value ΔH depends, chiefly, on the displacement of the maximum of the dynamic resonance curve, on the demagnetizing effect produced by eddy currents in the screen of the sample, and on the impulse delay of the detecting signal of the nuclear magnetic resonance in the amplification and shaping circuits.

Calculations and experiments show that when the rate of magnetic field intensity change is $\dot{H} = 4 \times 10^3$ Oersted per sec., when the non-uniformity of the field reaches 3×10^{-4} per cm., with the wire screens used, and with a pass band of the low-frequency amplification circuits of 5 kilocycles, the value of ΔH is within the range of 0.5-1.0 Oersted. In the case of a magnetic field intensity Of 150 Oersted this leads to a systematic error of the absolute measurement of $3 \div 6 \times 10^{-3}$. But if the correction is introduced the accuracy of absolute measurements reaches $1 \div 2 \times 10^{-3}$.

With relative measurements and when the value $\dot{H}$ remains constant (2.10^{-2}) from cycle to cycle, the results of the measurements are reproducible with an accuracy better than 5×10^{-4} in the measurements of small fields. In the case of fields of more than 1,000 Oersted the accuracy of H_{inst} measurements is better than $1 \div 2 \times 10^{-4}$.

For absolute measurements of the dependence of the frequency f(t) on the magnetic field intensity H(t), it is sufficient to know the absolute values of H_{inst} with an accuracy exceeding $1 \div 2 \times 10^{-2}$, while the accuracy of measurements of the constancy of the relation between f(t) and H(t) must be $3 \div 5 \times 10^{-4}$. This is explained by the fact that the optimum (for the proton synchrotron) relation between f(t) and H(t) is obtained by observing the beam position of the accelerated particles in the vacuum chamber.

While determining the required accuracy in measuring the value H_{inst} it is necessary to remember that for different proton synchrotrons the value $\partial f/\partial H$ changes within the limits of a cycle scores and even hundreds of times. Hence, if we take a fixed accuracy of measuring the deviation from the relation $f = \varphi(H)$, we will be able to reduce considerably the required accuracy of measuring the value H_{inst} during the greater part of the cycle.

In our apparatus for indicating the signals of the nuclear magnetic resonance we made use of a circuit with a valve generator[4], which responds to power absorption from the resonant circuit when the magnetic field intensity passes through the resonance value. The generator is made according to the modified Colpitts oscillator circuit. The generator valve is used simultaneously as a grid detector. When the magnetic field intensity passes the resonance value, pulse is excited in the plate circuit of the tube. The amplitude and the shape of the pulse are determined by

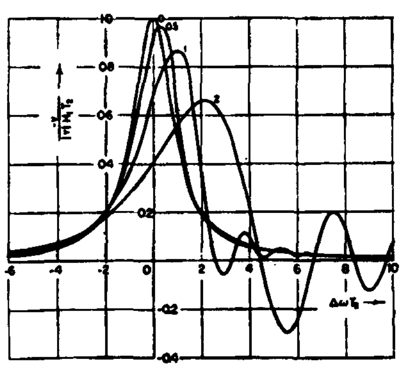

Fig. 1c. Nuclear resonance; theoretical curves for the case of absorption. (Iacobson, B.A. Wangness R.K.).

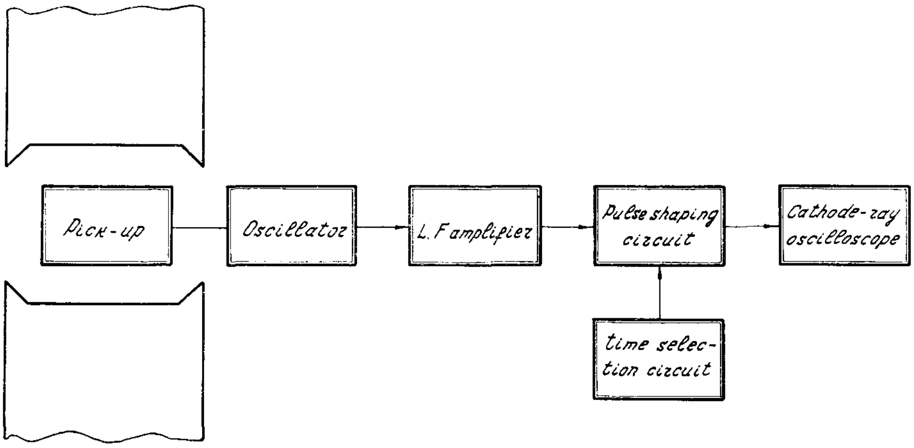

Fig. 2. Block-diagram of the device for measuring H by the method of nuclear magnetic resonance.

the conditions of measurement (non-uniformity of the field, rate of field change, magnetic field intensity, etc.), and the parameters of the generator and the sample (feedback, the matter used, the volume of the sample, etc.).

Obtaining a maximum ratio between the signal and the noise was one of the principal problems that we had to solve in our theoretical investigations and experimental work. For this purpose the generator circuit was provided with a device controlling the magnitude of the feedback capacity.

The coil of the generator circuit is wound on a glass bulb with the working substance inside. The coil is connected to the generator circuit by a coaxial high-frequency cable about 2 meters long and having a capacity of 56 pf. With such a cable we failed to obtain a maximum generated frequency higher than 12-14 Mc.

For measuring magnetic field intensities up to 13,000 Oersted we used water (protons), water solution of LiCl (isotope Li^7), heavy water (deuterons) or their mixtures as working substances.

Depending on the measuring range of magnetic field intensities, sample volumes vary between 5 cm^3 and 0.3 cm^3.

For reducing the possibility of parasitic signals arising at the output of the measuring device, its circuit is provided with time selection (gating) of the nuclear magnetic resonance signal (see fig. 2). The strobe-pulse is formed with the aid of the integrator of the H-value and the amplitude comparator, which are not represented on the block-diagram. In the pulse formation circuit the signals of the nuclear magnetic resonance are differentiated; by means of a trigger system a standard output pulse is formed, which serves to start the instantaneous frequency meter, for measuring the stability of the pick-up magnetic field intensity, etc.

To secure a wide frequency range, required for measurements in the range between 150 and 13,000 Oersted, the apparatus is provided with six generators switched on in turns. The inductance coils of these generators are combined in a single block; when measuring, this block is inserted into the operation area of the vacuum chamber of the proton synchrotron, without disturbing the vacuum.

A system of remote control is used for regulating the movement of induction coils, for switching on generators, for tuning the resonant circuit, and for the regulation of the generator feedback. The nuclear magnetic resonance signals are registered on the control oscilloscope in the operator's room.

To avoid disturbances, the inductance coils are encased in special wire screens in which eddy currents are very weak. The remaining elements of the apparatus are securely screened.

In addition to its principal function, the apparatus, which we described above, was also used to study the non-uniformity of the magnetic field of the proton synchrotron, to investigate the stability of the relation of the magnetic field intensities at different points in the magnet gap, and the relation of the intensities of stray fields and fields in the useful region of the gap.

Nuclear magnetic resonance was also used to calibrate and check the stability of the devices controlling the processes in the proton synchrotron.

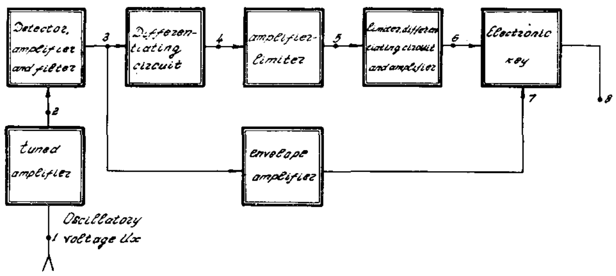

Fig. 3a. Block-diagram of the device based on the selection method.

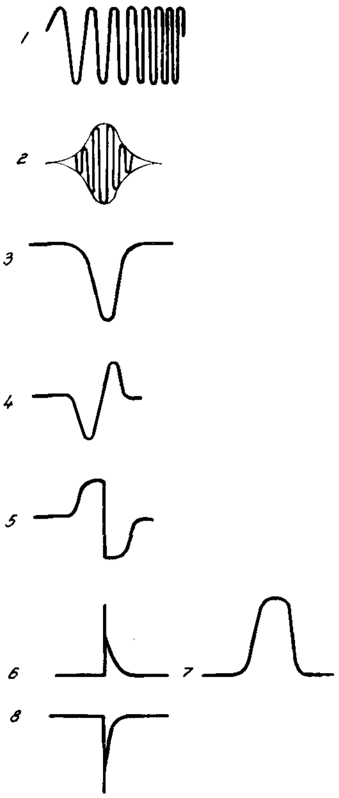

Fig. 3b. Time sequence of pulses at various points of circuit.

II. Measuring instantaneous frequency

a) *The method of selecting*

While measuring instantaneous values of variable frequency by the method of selecting, the moment of obtaining the maximum voltage amplitude is indicated on the resonant circuit. The measuring device based on the method of selecting, can be built on the basis of the block-diagram shown in fig. 3 a. The impulse diagram at various points of the circuit is shown in fig. 3 b.

When frequency-modulated voltage reacts on the resonant circuit, the frequency at which the maximum voltage on the resonant circuit is obtained, is displaced in relation to the resonance frequency, owing to dynamic processes in the circuit; and even a considerable reduction of the static passband of the resonance system does not raise the accuracy of measurements. The displacement of the maximum of the envelope at the output of the resonant circuit in relation to the resonance frequency of the circuit can be interpreted as a delay in time. When frequency changes slowly, the time delay is equal to double the value of the time constant of the circuit, but this delay is reduced when frequency changes at a higher rate.

For a given instability of the rate of frequency change $d\alpha/\alpha$, and an accuracy of indication of the envelope maximum at the output of the resonant circuit of $\delta f^* = F/A$, (F – static passband) there is an optimum passband of the resonant circuit $\Delta f_{opt} = 0{,}8\sqrt{A \cdot \alpha\,(d\alpha/\alpha)}$. Under these conditions, the resonant circuit with the passband Δf_{opt} ensures the maximum accuracy of measuring of instantaneous frequency at the given rate of frequency change.

In our devices, the accuracy of indication of the envelope maximum was brought up to one thousandth part of the static passband F of the resonant circuit (A = 1000).

The possibility of accurately indicating the envelope maximum enabled us to use resonant circuits with a large static passband and correspondingly insignificant delay in time.

For a more accurate indication of the envelope maximum we used a differentiating RC-circuit with a very small time constant, and amplifiers with bilateral limitation, which increased by 2×10^5 times the slope of the differentiated signal in the zone near the zero voltage. This brought about such an intensification of various disturbances that it was necessary to apply gating in order to separate the useful signal. The envelope of high-frequency oscillations, obtained after voltage detection at the output of the resonant circuit, was used as a strobe signal (curve 3 fig. 3 c).

If the amplitude of the input frequency-modulated signal is not constant, there is a possibility of an error in frequency determination, which is proportional to the instability in the rate of amplitude change of the high-frequency oscillations. In the presence of amplitude pulsations of the measured frequency-modulated oscillations a broad-band amplifier with automatic gain control was introduced into the measurement circuit; this amplifier provided a wide range in which the amplitude of the output signal did not depend on the amplitude of the input signal.

When it is necessary to cover a wide range of frequencies, for instance, in measuring the modulation characteristics of the master frequency-modulated oscillator in the frequency control system of the proton synchrotron, we propose to use frequency conversion and have a resonant circuit with constant adjustment. This makes it possible to raise the stability of the resonance frequency of this circuit.

For more simple devices, in which the range of frequencies to be overlapped is not wide, devices were designed with circuits having a switch-over resonance frequency. One of such devices ensured an accuracy of 2×10^{-4} in frequency measurement, with a rate of changes of 30 Mc per second, in the range 1-2.5 Mc.

In this device the resonance circuit was placed in a thermostat, where the temperature was maintained with an accuracy of 0.2°. The static passband of the resonance circuit was 30 kilocycles.

b) *The method of gating*

The method of gating is based on the comparison of the frequency to be measured and the constant standard

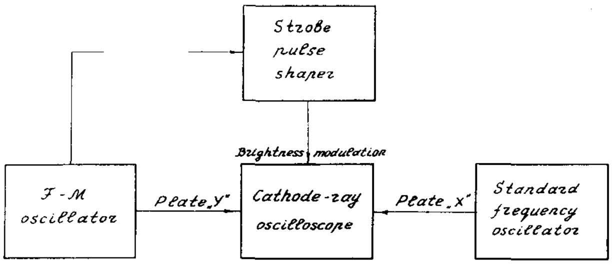

Fig. 4. Block-diagram of the device for measuring instantaneous frequency by "gating" method.

frequency at a fixed moment; the coincidence between the frequency of frequency-modulated signals is measured and the standard frequency is indicated by a minimum change of the phase difference between the frequency-modulated oscillation being measured and the oscillation of the standard frequency over a definite time interval.

An ordinary cathode ray-tube is used as an indicator of the changes in the phase difference of oscillation.

The block-diagram of the device for measuring the instantaneous frequency by means of gating is shown in fig. 4.

Frequency-modulated oscillations to be measured and oscillations from the standard range generator are applied to the deflecting plates of the cathode-ray tube. As a result of this, a picture of a rectangle with an uniformly lighted surface appears on the screen of the tube. If we cut off the electron beam and then open it for a short time by means of a strobe-pulse, we shall get on the screen of the tube Lissajous figures with lines of various thickness, depending on the time when the gating pulse appears and on its duration. With the electron beam turned on at a moment when the instantaneous values of constant and variable frequency coincide, a figure appears on the screen of the tube which is very much like an ellipse. It is assumed that the gating pulse is always longer than one period of the oscillation, under investigation.

As distinct from the case with similar constant frequencies or frequencies in integral ratio, when closed figures are traced by the electron beam on the screen of the tube, in the given case open curves appear on the screen. Continuous changes in the instantaneous value of the phase shift between oscillations will result in successive changes of the contours of the elliptical figure traced by the electron beam.

Indeed, there will appear on the screen of the c-r tube an ellipse with indistinct contours. To obtain a reading, it is necessary that the gating pulse be excited at a point corresponding to the coincidence of the standard frequency and the frequency to be measured, or that the standard frequency be altered with the gating impulse remaining fixed. There will appear on the screen of the c.r. tube either an ellipse with a broad indistinct contour, or an ellipse with a thin line shape. In the latter case, when the line is the thinnest, the standard and changing frequencies coincide.

If a definite connection between the duration of the gating pulse τ and the modulation rate of frequency α is observed, the error of measurements will be the smallest. The optimum duration of the gating pulse τ_0 is chosen in order that in the course of time τ_0 the phase difference between oscillations should change by an angle φ, which is the minimum necessary for visually fixing the changes in the thickness of the ellipse line. The value τ_0 is determined from the formula $\tau_0 = 7.4 \times 10^2\sqrt{\varphi_0/\alpha}$. For ordinary cathode-ray tubes, the value of the minimum difference of phase, φ, is estimated to be 3°. To this phase difference corresponds a two-fold extension of the line ellipse. At $\varphi = 3°$

$$\tau_0(\text{sec}) = 0.13/\sqrt{\alpha \quad \text{cycles/sec.}}$$

The absolute accuracy of measuring the instantaneous value of frequency by means of this method does not depend on the frequency being measured, and is 400 cycles.

The advantages of measuring instantaneous values of frequency by means of gating lie in the simplicity of this method and the possibility of employing standard devices.

c) *The method of "beating"*

By means of frequency conversion, it is possible to obtain oscillations with an instantaneous frequency equal to the difference between the varying frequency being measured and a constant reference frequency. The voltage on the mixer output is proportional to $\cos[\varphi(t) + \varphi_0]$, the varying phase is an integral in time of the instantaneous difference frequency, and the constant phase φ_0 takes into account initial phase relations of frequency-modulated oscillations and oscillations of constant reference frequency.

Fig. 5 a gives calculated curves showing changes in the voltage at the mixer output when frequency-modulated oscillations and constant frequency oscillations are supplied to the mixer. The figure shows that for any phase φ_0, which is an arbitrary value for every modulation cycle, the curve is symmetrical in relation to a vertical line corresponding to the moment of frequency coincidence.

When the phase φ_0 is unstable, a whole bunch of curves appears which makes it difficult to read the moment of frequency coincidence.

There is a method of stabilizing the phase φ_0 by means of synchronization prior to the moment of coincidence of the frequencies of the reference generator oscillations and the oscillations the frequency of which is being measured[5]. Before the very moment of frequency coincidence, the synchronization circuit is broken, and on the screen of the cathode-ray tube we can see just one curve from those shown in fig. 5 a. This method, however, causes an undesirable outside influence on the reference generator,

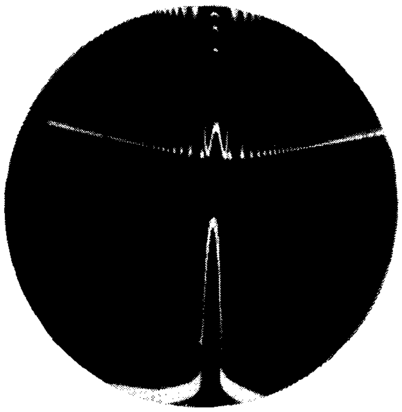

Fig. 5c. Voltages on the mixer output (upper curve) and output of the device (lower curve).

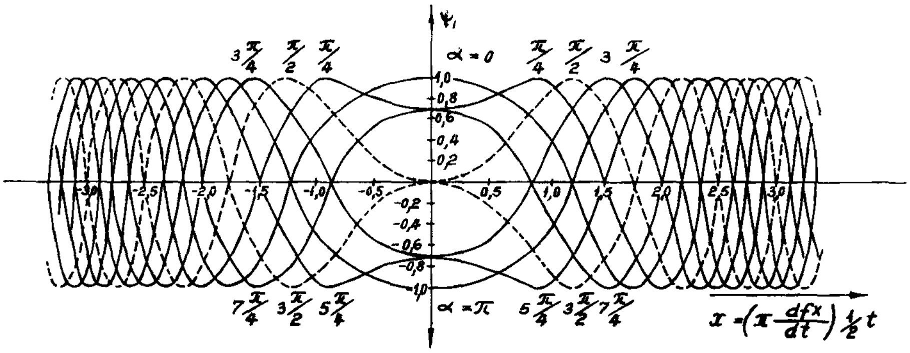

Fig. 5a. Function $\psi_1 = \cos(\pi\,df_x/dtt_2-\alpha) = \cos(x^2-\alpha)$ representing the mixer output voltage.

requires a low-quality oscillation circuit of the reference generator for its efficient synchronization by frequency modulated oscillations, etc.

A method was worked out and tested which made it possible to obtain, at the moment of frequency coincidence (reference and measured), a zero voltage, no matter what the initial phase φ_0 is.

The block-diagram of the measuring device designed according to the beating method is shown in fig. 5 b.

The frequency-modulated oscillation, the instantaneous frequency of which is to be measured, at a given moment, is applied to the inputs of two similar mixers; other inputs of these mixers are fed by oscillations of the same constant reference frequency, but with a phase shift of 90°.

At the output of the mixers voltages arise whose instantaneous frequencies are equal to the difference between instantaneous frequency of the frequency-modulated voltage being measured and the frequency of the reference oscillator. Then, by means of RC-circuits, the voltages are differentiated, raised to the second power, and the resultant voltages for both channels are summed up.

As a result, for any initial phase φ_0, we get a voltage U_b proportional to the square of the difference between the measured instantaneous frequency $\omega_x(t)$ and the constant reference frequency ω_0 i.e. $U_b = [\omega_x(t) - \omega_0]^2$.

When the varying frequency and the constant reference frequency coincide, the output voltage U_b is zero. The moment when the output voltage is equal to zero can be determined with great precision by using an additional amplifier with amplitude limitation. By changing the frequency of the reference oscillator, it is possible to measure the instantaneous frequency of frequency-modulated oscillations at any required moment.

Fig. 5 c shows oscillograms of voltages from one of the mixers (upper curve) and at the output of the circuit (lower curve), obtained by a double-beam oscilloscope. Oscillograms were obtained at $\alpha = 40$ Mc per second and $f = 2$ Mc.

Ring circuits, each including four germanium diodes, were used for raising voltages to the second power and also as mixers.

Tests made in the frequency ranges from 500 kilocycles to 10 Mc, with rates of frequency changes from 5

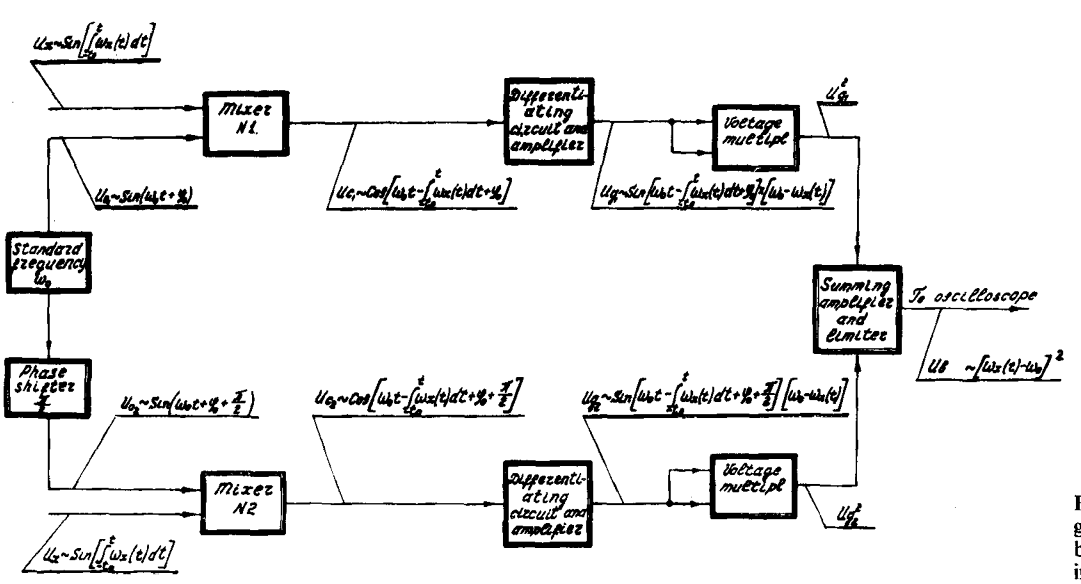

Fig. 5b. Block-diagram of the device based on the "beating" method.

to 50 Mc per second, showed that the accuracy of the method lies within the limits of $1\text{-}5 \times 10^{-4}$.

A device for measuring instantaneous frequency was also designed, based on the method of measuring the increment of the phase of the measured oscillations over a definite period of time; the characteristic of this instrument was given by Chase[6]. To raise the accuracy of measurements up to 3×10^{-4}, the instantaneous rate of frequency modulation α was measured.

It must be noted that the practice of adjusting the elements of the electronic system of proton synchrotrons revealed the necessity of extending the region of dynamic measurements. It appeard necessary to measure instantaneous values of slowly-changing voltages with an accuracy of $1\text{-}2 \times 10^{-4}$ and of the instantaneous rate of frequency modulation with an accuracy of $1\text{-}2 \times 10^{-2}$. We developed methods and also devices which make it possible to carry out such measurements.

Conclusions

The dynamic methods of measuring $H_{(t)}$ and $f_{(t)}$, described above, allow to measure the deviation from the relation between f(t) and H(t) in proton synchrotrons, and also to control modulation characteristics of the master oscillator in the frequency control system of such accelerators with a high degree of accuracy.

In view of the increased requirements of the accuracy of correspondence between f and H in accelerators with alternating-gradient focusing, we are now carrying on investigations in order to raise the accuracy of dynamic frequecy measurements by a factor of 10 to 100.

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DISCUSSION

J. P. Blewett: Concerning the last circuit discussed I understood that the output was zero when the frequency matches the standard frequency, but we saw a peak at that time on the oscillogram.

S. M. Rubchinski: The voltage is actually zero but you can display this point in the place you want.

R. Wideröe (to C. Schmelzer): Is it possible to detect by pick-up electrodes blow-up of the beam? If so you can arrange pick-up electrodes and compensate in your servo for the blow-up.

C. Schmelzer (to R. Wideröe): It is not possible to observe blow-up, i.e. increase of beam diameter without positional change of the centre of the bunches, without disturbing the beam, at least if you keep to simple arrangements, except may be for electron machines of very high energy, where one can observe visually (Bremsstrahlung).

F. A. Vodopianov (to C. Schmelzer): Did you investigate the influence of noise on the separate elements of the system?

C. Schmelzer (to F. A. Vodopianov): With ideal phase locked system, part of the noise would be partially compensated. This has, however, not yet been studied in detail.

F. A. Vodopianov (to C. Schmelzer): Pick-up electrodes do act as a feed-back system. In a system of that type, the noise appearing in the feedback determines the noise in all the system. Did you make an analysis of this point?

C. Schmelzer (to F. H. Vodopianov): The noise which can be partially compensated is noise in the generator and RF amplifying system, other noise exists in pick-up electrodes, and cannot be compensated because this is the place where you take your information from. The signal-to-noise ratio of the pick-up signal limits the use of beam control to fairly intense beams, as we have discussed in the paper.

V. Migulin (to C. Schmelzer): Do you know if your system of phase control has a tendency to self-oscillation? How do you prevent this?

C. Schmelzer (to V. Migulin): Phase-lock beam feed back systems are essentially oscillatory.

V. Migulin (to C. Schmelzer): Have you means to suppress parasitic oscillations in that system?

C. Schmelzer (to V. Migulin): This has not yet been studied.

J. Sharp (to S. M. Rubchinski): What type of squaring circuits follow the differenciators in the scheme you explain? What is the frequency and accuracy of squaring?

S. M. Rubchinski (to J. Sharp): Ring modulators were used as squaring circuits. Accuracy of 20 to 30% in multiplication or squaring is obtained but does not affect the overall accuracy figure of the system.

Frequency range:	500 Kc/sec to 10 Mc/sec
Rate of change:	5 Mc/sec up to 50 Mc/sec

G. K. Green: A problem of dynamic beam characteristics of practical importance: suppose in an AG machine that the equilibrium orbit is not perfect, due to magnetic saturation. Then the error in $\delta B/B$ increases and also at saturation the gradient versus radius is not constant. At x Kgauss the beam disappears and the beam can be at different points on the curve. The sign of the non-linearity can reverse and one wishes to know what happens for correcting. Snyder, Courant and I discussed these problems.

To determine the characteristics of the machine one must have position pick-up electrodes all around the machine, at least 4-5 per βtron oscillation that means 48 sets of x, y positions electrodes for the Brookhaven machine, and furthermore precise to 0.2″ (0.5 cm.).

These pick-ups are gated so that selected revolutions can be displaced in the control room or a cathode-ray tube. The most difficult part is the design of pick-up electrodes with their electronics. The x and y position versus time curves could be displayed on face of a Williams storage tube (this technique is well known). The computer takes up and indicates what to do.

J. Taieb (to C. Schmelzer): Le dernier diagramme présenté dans la première communication (beam feedback system with complete phase lock) est celui d'un oscillateur présentant deux boucles de contre-réaction.

La première boucle effectue un réglage lent de la phase par l'intermédiaire de Δr; la fonction de transfert présentant une résonance pour la fréquence des oscillations synchrotroniques, il paraît difficile de faire fonctionner cette boucle à des fréquences supérieures, et les caractéristiques de la partie électronique de la boucle s'en déduisent aisément.

La seconde boucle est celle qui utilise un discriminateur de phase pour comparer la phase de la tension sur l'électrode de détection et la phase de la tension accélératrice, et qui corrige cette dernière. La détermination de la fonction de transfert à donner à cette boucle me paraît plus délicate. Quelle doit être la caractéristique de fréquence souhaitable?

C. Schmelzer (to J. Taieb) : The feedback loop is in itself designed for a pass band from 3 to 10 MHz. The properties of the second loop have not yet been studied in detail, it seems however, that it is not necessarily unstable.

G. K. Green (to J. Taieb) : This servo loop includes the proton beam and therefore it is highly non-linear and not analyzable by the ordinary Nyquist diagramme or simple frequency plots.